



The Geological Surveys of Europe



GSEU
GEOLOGICAL SERVICE FOR EUROPE



Funded by
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EuroGeoSurveys

Strategic Research and Innovation Agenda: a Geological Service for Europe

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Acronyms

AI	Artificial Intelligence
BIM	Building Information Modelling
CCS	Carbon Capture and Storage
CRM	Critical Raw Materials
DNA	deoxyribonucleic acid
EGDI	European Geological Data Infrastructure
EGS	EuroGeoSurveys
EMODnet	European Marine Observation and Data Network
EPOS	Earth Plate Observing System
EU	European Union
FutuRaM	Future Availability of Secondary Raw Materials Project
GSE	Geological Service for Europe (operational entity under the umbrella of EuroGeoSurveys)
GSEU	Geological Service for Europe - CSA project
INSPIRE	Infrastructure for Spatial Information in Europe
ML	Machine Learning
NEP	National Exploration Programme
NGSOs	National and Regional Geological Survey Organisations
R&I	Research and Innovation
SRIA	Strategic Research and Innovation Agenda
UAVs	Unmanned Aerial Vehicles
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFC	United Nations Framework Classification for Resources
WEFE Nexus	Water-Energy-Food-Ecosystem Nexus

Executive Summary

EuroGeoSurveys is a not-for-profit association established in 1971, coordinating a network of 37 national and regional European Geological Survey Organisations (NGSOs). This network represents more than 10,000 geoscientists, data experts, and advisors, mandated to deliver data, information, and expertise on geology (surface and subsurface) and natural resources across their marine and onshore territories.

This document constitutes the Strategic Research and Innovation Agenda (SRIA) 2026 of the GSEU Project. It provides the scientific and innovation framework for the transition towards a permanent Geological Service for Europe, to be established in 2027 as the operational arm of EuroGeoSurveys. This revised version, updated from the GSEU SRIA published in 2025, integrates evolutions in the European socio-economic and geopolitical context, as well as recent scientific and technological trends, notably artificial intelligence.

The revised SRIA provides a framework for mobilising the collective scientific capacity of Europe's Geological Surveys organised through the Geological Service for Europe. It builds on the fundamental role of Geological Surveys as custodians of long-term geological knowledge and public scientific expertise, while recognising the need to transform this knowledge into integrated, accessible, and policy-relevant information.

A key ambition of the Geological Service for Europe is to move from producing geological information towards delivering integrated expertise dedicated to decision-support services. This requires stronger links between research, long-term observation, data infrastructures, and policy implementation, as well as closer collaboration with European institutions, national and regional authorities, academia, industry, and civil society.

The SRIA aims to contribute directly to the implementation of several key European legislation and policies.

Europe's policy landscape has changed significantly in the past years. The green and digital transitions remain central but are now embedded in a more urgent agenda of industrial competitiveness, economic security, defence readiness, energy independence, and resilience.

- Critical Raw Materials Act: national exploration programmes and improved knowledge of domestic CRM.
- Net-Zero Industry Act: geological data and storage assessments supporting EU CO₂-injection objective.
- Water Resilience Strategy: harmonised groundwater knowledge, monitoring, and forecasting.
- Electrification Action Plan: improved geological data to accelerate geothermal deployment.
- Preparedness Union Strategy: authoritative geoscience for risk anticipation and critical-infrastructure protection.
- Defence Readiness 2030: secure access to strategic resources and resilient infrastructure.

The SRIA revision is driven by:

- Changing economic and geopolitical context, placing European sovereignty at the forefront.
- Rapidly evolving technological landscape, notably the rise of artificial intelligence, Space- and ground-based observation technologies, geophysics advances, strengthening of open digital infrastructures and data platforms.
- Increasingly visible effects of climate change (droughts, floods, extreme events).
- Need to strengthen European economic sovereignty and reduce excessive dependencies.

This SRIA contributes to the implementation of the upcoming FP10, Pillar II “Competitiveness and Society” notably the priorities:

- Climate, Energy and Mobility.
- Industry and Space.
- Bioeconomy, Food and Natural Resources.
- Security, Defence and Resilience.

A Scientific Strategy based on Eight Major Goals

- GOAL 1: Understanding the Subsurface - Geological Knowledge (USG).
- GOAL 2: A Sustainable European Geoscience Data and Innovation Ecosystem - EGDI-e (DIG).
- GOAL 3: Energy Transition & Decarbonisation (ETD).
- GOAL 4: Responsible Raw Materials (RRM).
- GOAL 5: Sustainable Management of Groundwater in a Climate Change Context (GW).
- GOAL 6: Managing Geohazards and Environmental Risks (MGER).
- GOAL 7: Urban Geology, Land Planning, and Geoheritage (URB/LUP/HER).
- GOAL 8: Societal and Economic Impact (SEI).

Ultimately, the ambition of this SRIA is to establish subsurface sciences as a strategic component of European policy and decision-making. A permanent Geological Service for Europe, supported by a strong network of national geological surveys, can provide the long-term, independent, and science-based knowledge needed to manage continental and marine geological resources and environments responsibly.

Introduction

Who are we?

EuroGeoSurveys is a not-for-profit member association, established in 1971, providing vital subsurface knowledge to support Europe's competitiveness, social well-being, environmental management, and international commitments. EuroGeoSurveys coordinates a network of 37 national and regional European Geological Survey Organisations (NGSOs). The NGSOs are mandated to deliver data, information, expert knowledge, and advice on the geology (surface and subsurface) and associated natural resources in their respective marine and onshore territories. The network forms a workforce of >10,000 geoscientists, data experts, and advisors. Collaboration is governed in expert groups and strategic task forces including Earth Observation and Geohazards, Geochemistry, Geoenergy, Geoheritage, Geological Mapping and Modelling, Geophysics, Marine Geology, Mineral Resources, Spatial Information, Urban Geology, Water Resources, and International Cooperation and Development.



Figure 1: 37 EuroGeoSurveys Member countries, >10,000 geoscientists, data experts, and advisors.

What is our Mission?

EuroGeoSurveys addresses European challenges in the field of geosciences and collaborates on projects that inform European and national policy for the benefit of all European citizens and stakeholders. Our **mission is to enable sustainable and responsible use of the Earth's subsurface environment and resources**. The broad fields of application include effective land-use management, environmental monitoring (e.g., groundwater, soils), infrastructure planning, exploration and development (e.g., raw materials, geoenergy, underground storage), hazard assessment, risk mitigation, and more.

Our Position in the European Policy Landscape

Europe's policy landscape has changed significantly in the past two years. The green and digital transitions remain central but are now embedded in a more urgent agenda of industrial competitiveness, economic security, defence readiness, energy independence, and resilience. The Competitiveness Compass identifies innovation, decarbonisation, and security as mutually reinforcing priorities, while the Clean Industrial Deal positions decarbonisation as a driver of industrial growth. Within this agenda, the subsurface is a strategic European asset. Geological resources, storage capacities, and authoritative subsurface information underpin our understanding of CRM potential, secure energy, industrial carbon management, geothermal deployment, groundwater security, resilient infrastructure, and protection from geohazards.

NGSOs are publicly mandated to collect, preserve, interpret, and provide authoritative knowledge of their territories. These organisations encompass more than 10,000 specialists as well as extensive national data, expertise, laboratories, and infrastructure. Through their membership in EuroGeoSurveys, this network provides a unique mechanism for connecting national implementation with European policy objectives. For example, the roles of NGSOs are increasingly embedded in the following EU legislation and policy:

- **Critical Raw Materials Act:** national exploration programmes and improved knowledge of domestic CRM.
- **Net-Zero Industry Act:** geological data and storage assessments supporting the EU CO₂-injection objective.
- **Water Resilience Strategy:** harmonised groundwater knowledge, monitoring, and forecasting.
- **European Ocean Pact:** unified reference framework for all ocean-related EU policies adopted in 2025
- **Electrification Action Plan:** improved geological data to accelerate geothermal heating, cooling, and energy deployment.
- **Preparedness Union Strategy:** authoritative geoscience for risk anticipation and critical-infrastructure protection.
- **Defence Readiness 2030:** secure access to strategic resources and resilient infrastructure.

European and national authorities increasingly require harmonised data, cross-border assessments, common methodologies, and scientific advice for permitting, investment, planning, monitoring, and reporting. EuroGeoSurveys is uniquely placed to mobilise Europe's public geological capability to meet

Towards a Comprehensive Geological Service for Europe

A Vision to Capitalise Europe's Geological Information and Expertise

Europe possesses extensive geological knowledge, world-class public expertise, and substantial nationally held data and infrastructure. However, this capability remains distributed between countries, varies in coverage and maturity, and is frequently mobilised at European level only through temporary projects.

Many policy and investment challenges cannot be addressed effectively within national boundaries. Mineral systems, sedimentary basins, groundwater bodies, geological hazards, and potential storage formations extend across borders. Effective implementation of EU policy therefore requires coherent European information alongside detailed national knowledge.

Existing European cooperation has demonstrated that NGSOs can jointly deliver harmonised data, common standards, cross-border interpretations, and pan-European assessments. Nevertheless, project-based funding does not provide the continuity required to maintain these products, update them as new information becomes available, respond rapidly to policy needs, or retain the expert networks developed through successive programmes. The first edition of this SRIA identified the absence of incentives and structures for the continuous integration, harmonisation, and maintenance of European geological information as a central gap. EuroGeoSurveys is therefore progressing from the conceptualisation of a Geological Service for Europe towards its establishment in 2027 as the operational service arm of EuroGeoSurveys¹. The Geological Service for Europe will not constitute a separate regulatory authority and will not replace or bypass NGSOs. It will mobilise their collective capacities to provide a permanent framework through which national capability can be reinforced and applied to common European priorities.

The Geological Service for Europe will act as a force multiplier by:

- connecting national expertise, data, and data infrastructure while preserving national mandates and ownership;
- enabling all participating countries to access shared expertise, standards, and European-level services;
- delivering interoperable datasets and coordinated cross-border and pan-European assessments;
- strengthening national capacity through knowledge exchange, common methods, and institutional cooperation;
- reducing duplication and maximising the return on national and EU investment; and
- converting geological knowledge into trusted intelligence for policy, permitting, planning, and investment.

The Geological Service for Europe will provide an enduring bridge between research and operational delivery. Research and innovation will remain essential for maintaining authoritative knowledge and developing new methods, but they will be connected to permanent services that preserve, update, and apply the resulting data, models, and expertise.

The Geological Service for Europe

The Geological Service for Europe will be EuroGeoSurveys' operational service arm and the geoscientific reference partner for European institutions. It will mobilise the collective capability of member NGSOs under member-driven governance, subsidiarity, and national responsibility:

Information

Provision and maintenance of harmonised, authoritative, and regularly updated geological data, maps, models, and knowledge products through EGDI² and connected European data systems.

Research

Coordination of applied, policy-driven research that substantiates process insights and system understanding, reduces uncertainty, assesses risks, and develops new services for common European needs.

Advice and strategic support

Mobilisation of expert networks to support EU and national policy implementation, cross-border assessment, permitting, investment, international cooperation, and capacity building.

These functions represent an evolution from the periodic delivery of project outputs towards a permanent European service capability. The emphasis will be on reliable, reusable, and policy-relevant products and services that respond to clearly identified user needs.

The European Geological Data Infrastructure is fundamental to this model. EGDI is the common digital infrastructure of the Geological Service for Europe. It will connect nationally held information with European dataspace and provide the continuity, governance, and technical capacity needed to maintain datasets, models, tools, and transparent data-to-decision services.

Future Geological Service for Europe services may include:

- Harmonised geological frameworks and European-scale models;
- Raw-material inventories, prospectivity assessments, and support for national and cross-border exploration;
- Geoenery resource, planning, permitting, and risk-reduction services;
- CO₂ and H₂ storage capacity, and storage-readiness assessments;
- Groundwater monitoring, forecasting, and water-resilience services;
- Geohazard and critical-infrastructure risk information; and
- Technical cooperation and capacity building with partner countries.

These onshore-offshore services will enable European institutions, Member States, associated and third countries to draw on established national capability while obtaining coherent European-scale information and advice.

A Public Service Supporting Europe's Policy Agenda, Sustainable Development Goals, Strategic Autonomy, and Economy

Geological resources and subsurface regulation remain primarily national responsibilities. The Geological Service for Europe will respect these competences while providing common information, expertise, and cross-border coordination where European objectives cannot be achieved efficiently through national action alone.

Geological information is increasingly strategic public infrastructure. It reduces uncertainty, supports spatial planning and permitting, identifies resource and storage opportunities, improves risk management, and strengthens investor confidence. In the current policy context, these functions support not only climate and environmental objectives, but also competitiveness, energy and material security, defence readiness, and resilience.

The Geological Service for Europe will therefore contribute to:

- sovereignty, security, and reduced strategic dependencies;
- industrial competitiveness and investment de-risking;
- efficient implementation of European and national policy;
- stronger national capability through shared expertise and knowledge transfer;
- territorial cohesion and access to specialist European capacity;
- responsible management of competing subsurface uses;
- preparedness, infrastructure resilience, and geohazard risk reduction; and
- strategic international cooperation.

The Geological Service for Europe will connect national authority with European economies of scale, shared infrastructure, and collective expertise, providing an implementation capability rather than an additional regulatory layer.

Horizon Europe GSEU Project: Major Steps Towards a Geological Service for Europe

GeoERA demonstrated the value of coordinated transnational geological research. Building on this foundation, the 5-year Horizon Europe GSEU project, launched in 2022 with 48 organisations from 36 countries, has developed harmonised information, methodologies, and services across groundwater, geoenery, raw materials, coastal resilience, offshore geology, and foundational geological mapping and modelling, delivered through EGDI.

GSEU has provided the scientific, technical, and collaborative foundation for a permanent Geological Service for Europe. It has:

- Strengthened EGDI and developed common data models, vocabularies, and standards;
- Advanced pan-European mapping, 3D modelling, and harmonised thematic datasets;
- Produced decision-support products for raw materials, geothermal energy, CO₂ storage, groundwater, and coastal areas;
- Expanded collaboration, user engagement, training, and knowledge transfer across NGSOs; and

- Tested the technical, organisational, and service concepts required for a permanent Geological Service for Europe.

Development has now moved beyond technical feasibility. EuroGeoSurveys members have agreed an implementation pathway under which the Geological Service for Europe will be established in 2027 as the service arm of EuroGeoSurveys, using its existing legal identity, governance, and membership while creating a dedicated operational framework for European geological services.

The transition from GSEU to the Geological Service for Europe requires:

- Clear governance and decision-making;
- A prioritised, user-driven service portfolio;
- Sustainable operation and development of EGDI;
- Dedicated programme and service-management capacity;
- Transparent project, quality-assurance, and data-governance processes; and
- Sustained institutional engagement and long-term financing.

Future projects involving EuroGeoSurveys and its members will operate within the Geological Service for Europe framework and contribute to a coherent portfolio of reusable services. The aim is not to centralise national geological work, but to ensure that European and national investment produces lasting data, standards, infrastructure, expertise, and operational capacity.

This SRIA provides the scientific and innovation framework for that transition, identifying the knowledge, services, and collaboration required to transform Europe's distributed geological capability into a sustained public service supporting competitiveness, sovereignty, resilience, and responsible subsurface management.



Figure 2: The path towards a Geological Service for Europe.

Ultimately, a **permanent Geological Service for Europe** requires sustainable resourcing to ensure that EuroGeoSurveys and the NGOs can continue to support the Green Deal³ and the European Ocean Pact⁴ through our actions, maintaining and improving key European datasets and knowledge, delivering geoscience-based policy support, mentoring and training geoscientists, and promoting best practices and knowledge sharing.

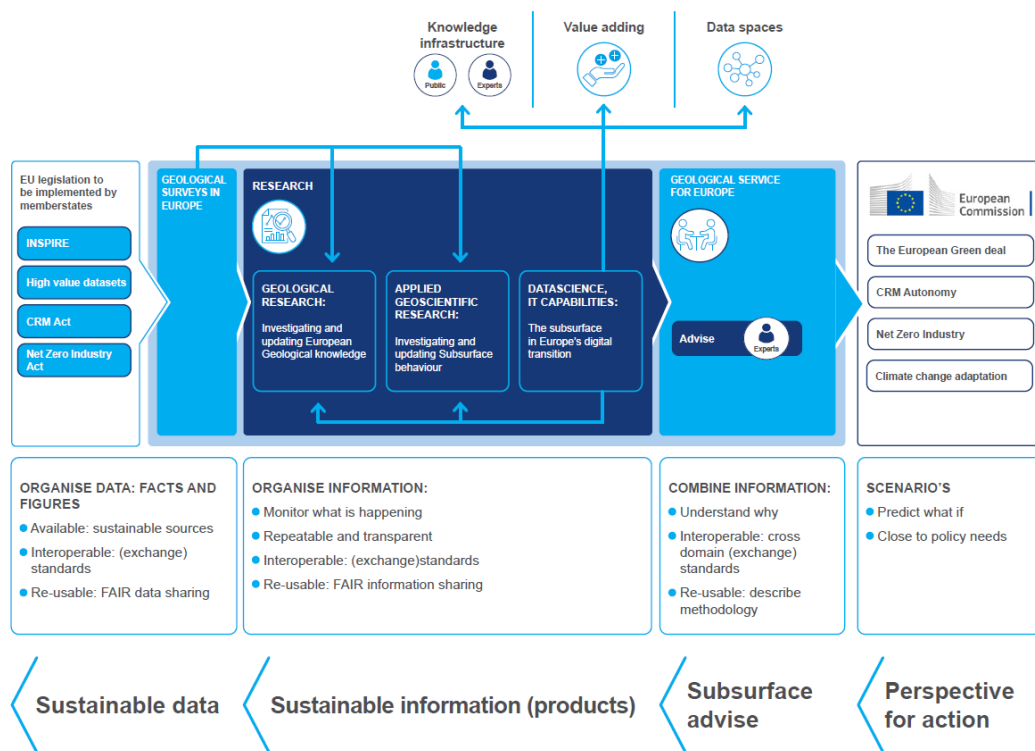


Figure 3: The role of the European Geological Surveys and a future Geological Service for Europe in supporting science-informed EU policy.

An updated SRIA to fit with the European policy and priorities

A Changing Socio-Economic and Geopolitical Environment

The revision of the GSEU SRIA prepared in 2024–2025 is driven both by the changing economic and geopolitical context, which has brought European sovereignty issues to the forefront, and by the rapidly evolving technological landscape, particularly the rapid rise of artificial intelligence.

Since the previous version, the economic disruptions following the COVID-19 crisis and changes in geopolitical context have reinforced the need to strengthen the sovereignty of the European economy and reduce the risks associated with excessive interdependence. These developments have accelerated the transformation of the European energy model and economic model, leading to major changes in industrial policy strategies and mineral resource supply chains, and consequently requiring scientific and technological responses to evolve accordingly.

At the same time, the effects of climate change are becoming increasingly apparent across Europe, particularly through the intensification of extreme events, significantly increasing the severity of certain natural hazards. Changes in precipitation patterns, especially in southern Europe, are resulting both in longer periods of drought and increasing water scarcity, as well as in more frequent periods of heavy rainfall and increasingly sudden and severe flooding, particularly around the Mediterranean basin but also in Central Europe. These developments have led to a reassessment of some of the scientific priorities of the SRIA and to a stronger focus on issues related to climate change adaptation policies, as well as on reindustrialisation in the context of the green, energy and digital transitions.

Scientific Priorities Supporting Europe's Major Policies and FP10

The Green Deal and the range of policies and directives recently introduced require substantial and integrated R&I efforts. This SRIA aims to contribute to the successful implementation of European Green Deal policies and to achieving a sustainable future through a common Geological Service for Europe.

This document is also intended to contribute to the development of FP10, particularly to Pillar II “Competitiveness and Society”, and more specifically to the emerging priorities:

- Climate, Energy and Mobility
- Industry and Space
- Bioeconomy, Food and Natural Resources
- Security, Defence and Resilience

This Research and Innovation Strategy is structured around several major drivers:

The Green Transition and European Industrial Sovereignty Depend on Access to Mineral Resources

The development of renewable energy, alongside nuclear power, and the large-scale electrification of transport will considerably increase demand for mineral resources over the coming decades. Dependence on fossil fuels will inevitably be replaced by a growing dependence on metals, raising major challenges in terms of security of supply, sovereignty, costs, and environmental impacts.

The demand for metals driven by the energy transition will add to that generated by the digital transition. The recent revival of European raw materials policy calls for EuroGeoSurveys to support the implementation of new public policies in this field, notably by assessing Europe's potential for primary mineral resources and by supporting mineral resources diplomacy and cooperation with third countries, particularly in Africa.

The Subsurface and Its Resources: A Key Role in Climate Change Mitigation

The large-scale decarbonisation of energy systems and the need to regain sovereignty over the supply of low-carbon energy have profoundly changed priorities regarding the European energy mix.

Both shallow and deep geothermal energy are now considered essential components of Europe's energy transition. Underground storage of heat and energy carriers, particularly hydrogen, is also expected to expand significantly in the coming years.

The Need to Accelerate Climate Change Adaptation in Europe

EuroGeoSurveys and its members have a key role to play in the coming decades in addressing the challenges arising from the impacts of climate change and the need for societal adaptation. In terms of research and expertise, the Geological Service for Europe will contribute both to characterising the processes involved and anticipating future developments to assess associated risks, while also developing innovative approaches to mitigate or remediate their impacts.

At the same time, anthropogenic pressure on the environment and its resources, combined with urban growth, is increasing the vulnerability of territories to the effects of climate change.

Climate change is also expected to increase overall vulnerability to natural hazards, including landslides, ground collapse and subsidence, rockfalls, erosion, and shrink-swell behaviour of clay-rich soils. Coastal areas are particularly vulnerable to climate change, which is exacerbating risks associated with coastal flooding and erosion and leading to significant shoreline retreat across Europe.

These phenomena need to be monitored and modelled both over the long term to design and dimension appropriate adaptation measures, and over the short term to support crisis management during extreme events.

The global water cycle will be profoundly affected by climate change, with changes in precipitation patterns, particularly around the Mediterranean basin and in Central Europe. Climate change is already affecting long-term groundwater recharge patterns, requiring adaptation of water management strategies at the scale of major river basins.

These processes need to be monitored and modelled to provide the authorities responsible for meeting societal needs with the knowledge required to make informed decisions. Controlled groundwater management solutions need to be developed to adapt to these changing conditions.

The table below summarises the main European policies, legislative acts and strategic frameworks to which the SRIA will contribute.

Table 1: Current EU legislation and policies directly impacting the subsurface.

EU Legislation / policy	Goal
Critical Raw Materials Act (CRM Act) ⁵	Enhance self-sufficiency of mineral raw materials in the EU
Water Framework Directive (WFD) ⁶	Prevent and reduce pollution, promote sustainable water use, protect and improve the aquatic environment
Groundwater Directive (GWD) ⁷	Protect groundwater against pollution and deterioration
European Water Resilience Strategy (EWRS) ⁸	Ensure secure, clean, and affordable freshwater supply
Urban Wastewater Treatment Directive ⁹	Manage wastewater and adapt to climate change, supporting also nature-based solutions
Net-Zero Industry Act (NZIA) ¹⁰	Achieve carbon neutrality by 2045
Soil Monitoring Law ¹¹	Ensure healthy soils through soil monitoring and remediation of contaminated sites
Nature Restoration Law ¹²	Preserve and increase biodiversity and landscape resilience
INSPIRE Directive ¹³	Provide standardised geospatial information for sustainable development, public administration, public safety, and environmental decision-making
Marine Spatial Planning Directive ¹⁴	Promote the sustainable growth of the EU's Blue Economy, development of marine areas, and use of marine resources
Carbon Capture and Storage (CCS) Directive ¹⁵	Provide a regulatory framework for CCS, and support competent authorities and storage site operators so that CO ₂ can be safely stored underground
Renewable Energy Directive (RED) ¹⁶	Speed up the EU's clean energy transition by increasing the share of renewables in its energy mix (geothermal energy)
Ocean Pact ¹⁷	Protect the ocean, promote the Blue Economy, and support the well-being of people living in coastal areas

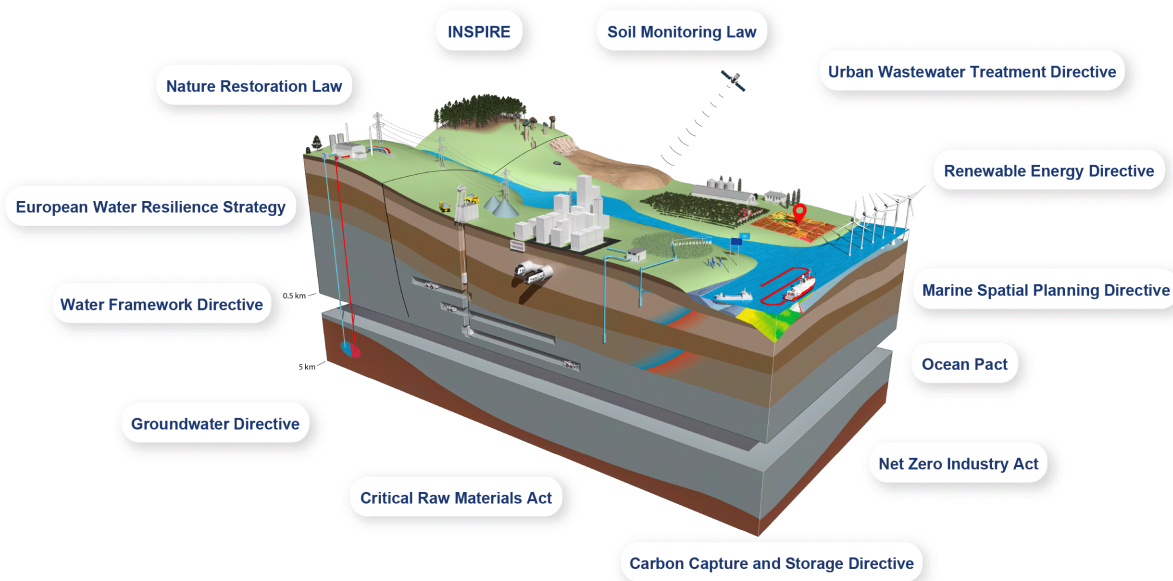


Figure 4: Competing subsurface uses are integrally connected with recent EU policies.

A SRIA Integrating Recent Scientific and Technological Trends

Beyond the evolution of public policy frameworks, the SRIA is strongly influenced by recent scientific and technological developments in the Earth sciences. Among these trends, the revision of the scientific strategy places greater emphasis on several key developments:

- *Artificial intelligence is already having a profound impact on the geosciences* and on subsurface information, providing new tools and methodologies to analyse vast amounts of data that are inherently heterogeneous, uncertain and incomplete, while opening up new opportunities for predictive modelling. The ability to combine and exploit multiple data sources can lead to more holistic and accurate representations of geological systems.
- *Recent advances in space- and ground-based observation technologies* (new geophysical methods, new hyperspectral sensors, micro- and nanosatellites, Copernicus services, etc.) are opening up new opportunities for the activities of Geological Surveys. These technologies can improve territorial monitoring, notably for the management of natural and anthropogenic hazards, mineral resource exploration, and soil monitoring.
- *The strengthening of open digital infrastructures and data platforms* is playing an increasingly important role in the activities of the Geological Service for Europe, particularly in hosting and disseminating geoscientific data, digital services, and environmental information. The development and use of such platforms require common standards, interoperability protocols, and data-sharing policies to ensure that data are accessible, understandable, and usable by all relevant stakeholders, including researchers, policymakers, and private companies, while being adequately protected where the nature of the data requires it.

A Scientific Strategy Built Around Eight Major Goals

Foresight activities and an analysis of EuroGeoSurveys' scientific positioning within the European ecosystem have identified eight major challenges covering the full scope of the organisation's activities. These challenges are intended to encompass the full spectrum of its scientific activities, from research to expertise and innovation:

- **Geology and subsurface knowledge:** this challenge lies at the core of the fundamental mission of a Geological Survey and aims to acquire, consolidate and provide an integrated understanding of the subsurface, increasingly through digital approaches.
- **Five major socio-economic and environmental challenges:** energy transition and decarbonisation; sustainable and responsible access to mineral resources; management of geohazards and environmental risks; sustainable groundwater management in a changing climate and the role of the subsurface in spatial planning and urban geology.
- **The digital information value chain and the associated platform (EGDI).**
- **Expertise for greater socio-economic impact,** through support to public policy and public engagement.

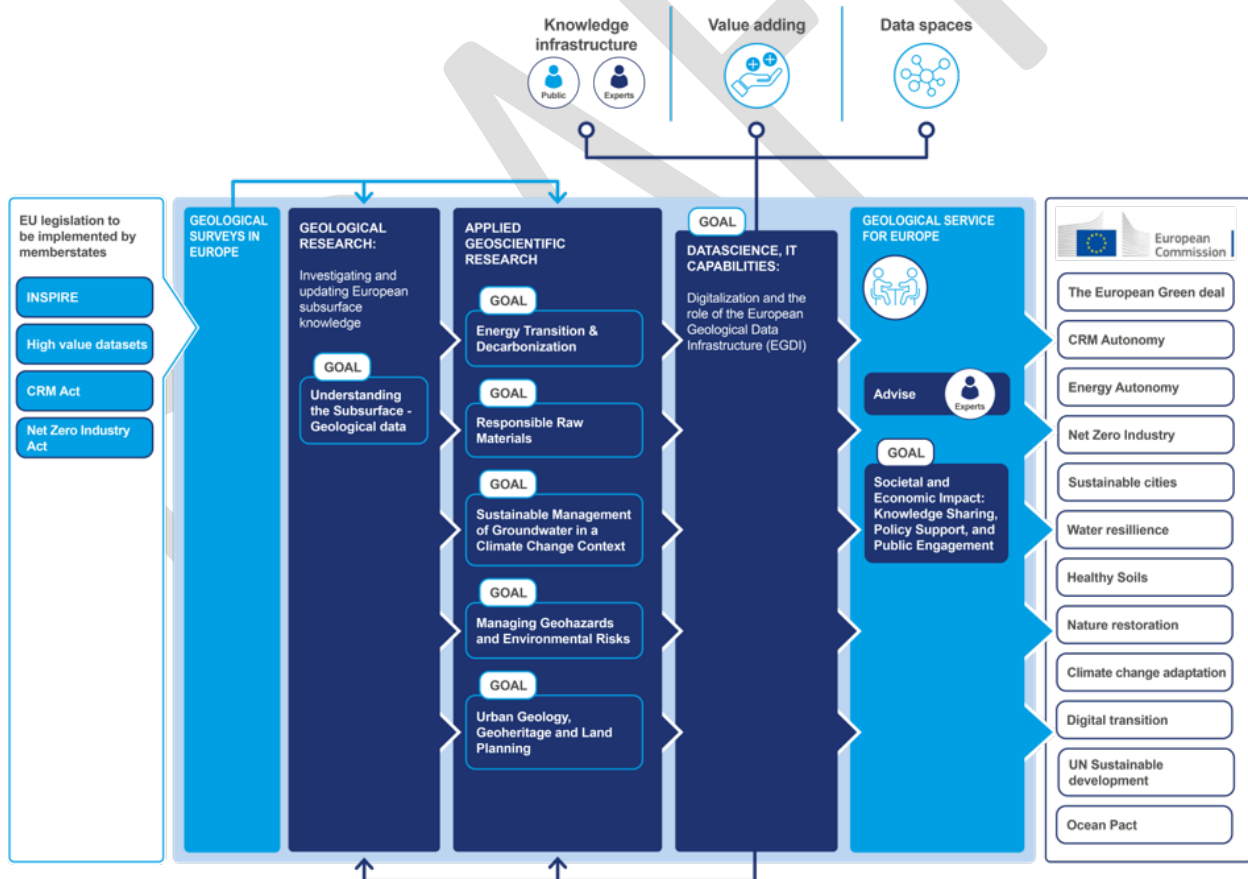


Figure 5: The structural elements of the EuroGeoSurveys SRIA and connections to science-informed EU legislation and policy.

Geoscientific and Digital Foundational Framework

GOAL: Understanding the Subsurface – Geological Knowledge (USG)

Responsible economic and environmental planning require precise geological information and knowledge about the subsurface – information that constitutes the foundation for all applications related to subsurface use and resources. To support such planning, 2D and 3D geological mapping is necessary. These maps and models are the foundation of all geological work, allowing geologists to transform data into meaningful knowledge about the structure, composition, resource endowment, and evolution of the Earth. The practical applications of these maps and models are enormous in scope, allowing:

- Access to mineral resources, including strategic and critical raw materials, surface and subsurface.
- Discovery and improved access and monitoring of groundwater resources.
- Define the interconnection between groundwater and surface water resources.
- Development of geoenergy potential (e.g. geothermal energy, heat and cold, offshore wind farms, energy storage).
- Mitigation of climate change impacts and other geohazards.
- Identification and preservation of geoheritage sites to support science, education, and tourism.
- Support coastal and marine research to improve knowledge and promote better maritime spatial planning and environmental protection of these environments.

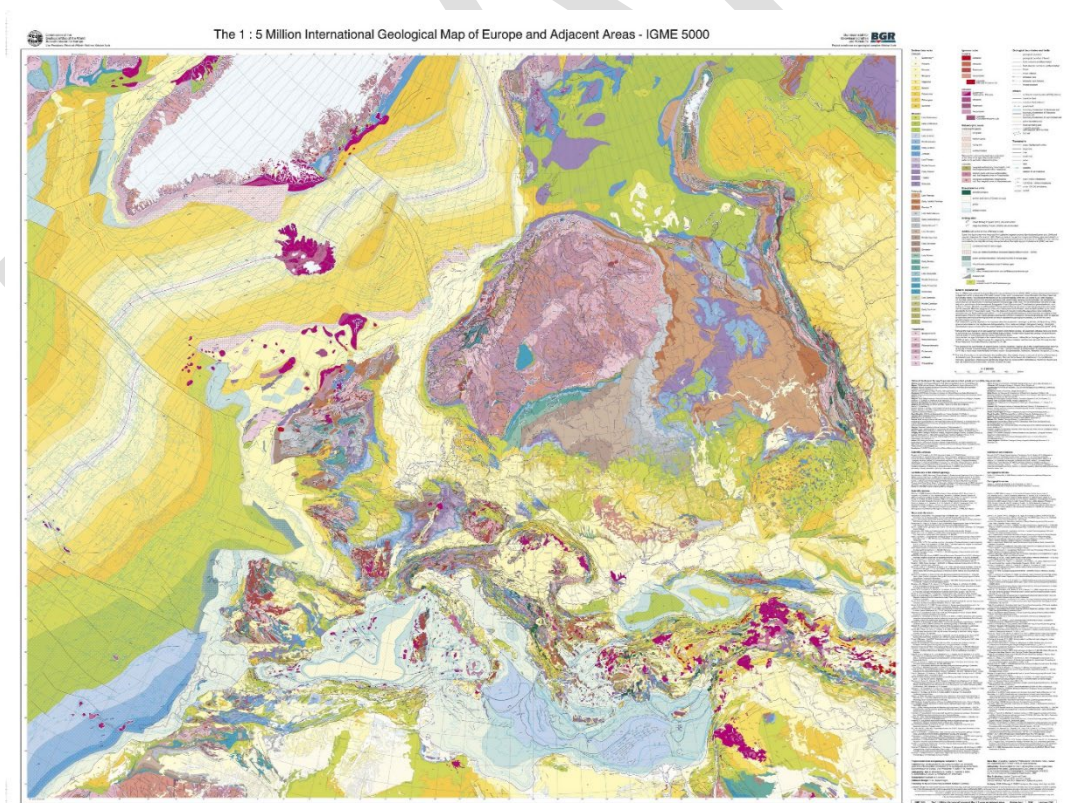


Figure 6: The 1:5 Million International Geological Map of Europe and Adjacent Areas – IGME 5000¹⁸ – a collaborative effort of the European NGSOs.

While financially resource intensive, geological mapping is a sound investment, returning benefit-cost ratios of 4:1 to > 100:1 in terms of, e.g., exploration investment, jobs, taxes, and royalties. However, investment at European scale has been limited. Transboundary, harmonised, basic geological datasets of appropriate scale and quality are still lacking for most European regions, and both the surface and subsurface knowledge of the European territory is heterogeneous in both quantity and quality. This presents major obstacles to delivering geoscience-based solutions to surface and subsurface-related enviro-economic challenges.

Effective implementation of new and anticipated European policy and legislation (e.g., CRM Act, Net-Zero Industry Act, Soil Monitoring Law, Renewable Energy Directive, Ocean Pact), will require continuously updated, high-quality geological datasets, maps, and models. As the nationally (and in some cases European) mandated authorities to deliver this data, the NGSOs have key roles in supporting the implementation of policies comprising the European Green Deal and related industrial policies.

Within the GSEU project, EuroGeoSurveys will deliver (amongst others) basic elements of a geological mapping and modelling framework, including data models (conceptual and physical), new and improved scientific vocabularies, an open-source toolbox for 3D geomodelling, and a metadata service for geological maps, map datasets, and 3D geomodels relevant at the European level.

These GSEU project outputs need completion of the frameworks for missing vocabularies (e.g., for Quaternary deposits and lithogenic information), a system for regional, transboundary correlation of lithostratigraphic units, and establishment of a collaborative platform for joint activities in 2D and 3D modelling. Use of this framework must urgently start by creating harmonised, transboundary datasets of European regions or at continental level in 2D and 3D at scales of 1:250.000 and beyond. Continuous updating and refining of datasets is necessary and will be possible only by embedding this activity in a stable institutional environment.

Beyond this, a modern and effective approach of (re)investing in Europe's marine and continental geological knowledge must be accompanied by innovation measures, e.g., new methods in geophysical data acquisition, ocean observation systems and ocean observation technologies, exploration of AI-based tools and machine learning for integration of large data volumes from different sources (geological, geophysical, geochemical) in 3D geomodelling, and development of algorithms for automated generalisation of 2D and 3D geological models. Moreover, innovative pathways of technical and organisational support of national and transboundary geological mapping initiatives should be explored.



Figure 7: Geological datasets, maps, and models lay the foundation for delivering on UN SDGs.

Priority USG1 – Reinvest in updating of geological information in Europe

Over the last two decades, most geological surveys have invested in digitisation and harmonisation of existing geoscientific data, information, and knowledge. The maps are now available as vector maps with attached databases showing mostly surface geology. However, detailed reconnaissance of the subsurface remains incomplete, with poor resolution, or outdated scientific concepts for many regions in Europe.

The collection, correlation and continuous update of continental and marine geological data and their interpretation, by establishing geological models (maps, sections and 3D- to 5D-models) and through expertise, is essential to meet the requirements of various stakeholders.

New European legislation (e.g., the Critical Raw Materials or Net-Zero Industry Acts) will require investment to collect additional data, information, and knowledge and to produce European-scale transboundary 3D models at the resolution needed to evaluate mineral and geoenergy resources as well as CO₂ storage potential, across Europe and with common standards.

Action USG1.1 – Establish a collaborative Geographic Information System platform

Expected outcomes:

- An open-source, integrated GIS-based platform with integrated scientific vocabularies, allowing for effective and transboundary collaboration of experts in the creation of new regional datasets.
- Defined workflows, training, and support for project teams.
- Guidelines defining minimum requirements for onshore and offshore geological mapping in Europe for different scales.
- A solid governance system to ensure storage, maintenance, and updating of the data.

Action USG1.2 – Create scientific vocabularies for missing themes to enable data harmonisation at European level

Expected outcomes:

- Scientific vocabularies for Quaternary near-surface deposits ('lithogenic units') and landforms, structural elements of rocks, and other themes, to support an ontology for geological baseline data.
- Online vocabularies, based on Simple Knowledge Organisation System and linked data technology, available through EGD.
- A technical and organisational framework for the governance, management, and updating of vocabularies including suitable front-ends, editorial boards, etc.
- A semantic reasoner for AI fact-checking and knowledge deduction for existing vocabularies, building on developments made in the GSEU project.

Action USG1.3 – Create regional, harmonised transboundary onshore and offshore datasets at a scale of 1:250.000 to 1: 1 million

Expected outcomes:

- Regional transboundary datasets, based on, e.g., lithotectonic units, as a fundamental classification element of legends with further subdivision according to lithology, age, genesis (environment, process), lithostratigraphic units, and others. E.g., (1) a small-scale dataset of the

European basement based on the IGME 5000 and lithotectonic map produced in the GSEU project, (2) a harmonised 1:1 Million Geological Map of Europe using the One Geology-Europe dataset and new data, based on the data model and vocabularies developed in the GSEU project.

- A semantic web-based system to manage regional, transboundary correlation of lithostratigraphic units in Europe, including a set of rules for the harmonisation procedure.
- Multiple integration of onshore and offshore regional geological datasets with applied geoscientific datasets in the fields of raw materials, groundwater bodies, potential geological hazards, geothermal energy, etc.

Action USG1.4 – Support new, and improve existing, national 2D and 3D geological mapping programmes

Expected outcomes:

- Documentation of best-practice examples for the organisation of mapping campaigns and multi-annual mapping programmes.
- A pool of experts ready to advise on transboundary geological mapping programmes both onshore and offshore, e.g. in support of the implementation of the CRM-focused “Regional programmes” which have been recently requested by DG GROW.
- Recommendation of (open-source-based) digital workflows and other technical aspects in data acquisition.
- Foster innovative incentive schemes at EU-level to support national and transboundary mapping programmes.
- Established network of highly specialised experts in the fields of, e.g., biostratigraphy, geochronology, mineralogy, geochemistry or petrology at NGSO level for mutual support in sample processing, data analysis, and interpretation from mapping campaigns.

Priority USG2 – Towards a European-scale 3D geological model

Knowledge of the European subsurface is critical to access resources and to assess and mitigate risks. A common approach at the European countries level is foreseen to achieve a coherent and multi-use description of the subsurface. However, the ways to access the underground and its parameters are often sparse and indirect. Geomodelling combines the available data and information from e.g., geology, geophysics, and geochemistry. The goal is to give a comprehensive and transboundary description of the subsurface in 3D and to contribute to the deployment of the European Digital Twin of the Ocean.

The ambition is to produce a 3D crustal-scale model of the main lithotectonic units to a depth of 5–10 km. The model will be built using the main existing syntheses (1:5 Million European geological map¹⁸, combined with national 3D models) and the most recent seismic profiles. The main interfaces to be incorporated include the major faults separating the main lithotectonic units, the basement-sedimentary cover boundary, and the crust-mantle boundary. However, when considering the uppermost part of the Earth’s crust in urban areas, an adapted approach is required regarding spatial resolution and input data as well as processing, description, packaging, and provision of relevant geological and hydrogeological 2D and 3D specialist data.

Action USG2.1 – Define common rules for the description of geological objects in 3D for integrating national geomodels at European scale

Expected outcome:

- Technical specifications and requirements to harmonise and make compatible 3D geological models at European scale.

Action USG2.2 – Set up a common, integrated platform to host and query 3D geomodels in relation with EGD

Expected outcome:

- A numerical repository to host, visualise, and query 3D geological models.

Action USG2.3 – Develop a European-scale 3D geological model

Expected outcome:

- A pan-European 3D Geological Model to serve user needs.

Action USG2.4 – Build high-resolution 3D digital geological models

Expected outcomes:

- Visualisation of complex subsurface conditions by integrating 3D geological models with existing infrastructure data, enabling clearer understanding of spatial relationships between geological formations and underground structures, building on developments from the GSEU project.
- Enhanced geological insights provided through detailed 3D models, enabling identification of key formations, rock properties, groundwater flows, and potential hazard zones.
- Optimisation of subsurface resource use through application of 3D models, allowing planners to efficiently allocate resources such as groundwater and geothermal energy, while minimising conflicting uses, e.g., tunnels, utilities, and natural resources.

Priority USG3 – New technologies for subsurface investigation and geomodelling

The ambition is to provide techniques and tools to strengthen the knowledge of the European continental and marine surface and subsurface and support the development of coherent geomodels at European level, to inform decision-making for applications that require 3D and 4D models (e.g., mineral exploration, urban subsurface works, vulnerability assessments, etc.). To achieve this, it will be crucial to combine multiple data types and sources, multi-methods, and multi-scale approaches to interpret subsurface structures and behaviour in 3D. Modern geophysics (e.g., electromagnetic UAV surveys, quantum gravimetry, electromagnetic technologies, optical fibre monitoring, micro gravimetric, micro seismics) provide a new range of techniques to improve investigation of the subsurface. Beyond sharing common methodologies and best practices, research efforts should also focus on developing and deploying R&I using a common framework and, wherever possible, open source. A key area of development is to build up an integrated semantic model (ontology) in geological basic data (including geology, geophysics, geochemistry, seismology, etc.), to better serve applied geosciences.

Action USG3.1 – Set up innovative ground-based and airborne geophysical methods in geological surveying and exploration

Expected outcomes:

- New investigation methods combining data acquisition from the ground to satellite.
- An ‘acquisition-processing-modelling’ value chain based on multi-scale geophysics, remote sensing, digital geology, Machine Learning (ML), and big data processing.
- Geophysical methods adapted to accessibility and noise constraints of the urban environment.
- Distributed acoustic sensing solutions to survey and monitor urban events.

Action USG3.2 – Develop new methods and tools based on geomodelling and AI to integrate data and information from different sources (e.g., geology, geophysics, geochemistry)

Expected outcome:

- Automated and semi-automated solutions to construct integrated 3D geomodels designed for specific user needs building on deliverables of the GSEU project.

Action USG3.3 – Develop common 3D geomodelling methodologies and R&I framework

Expected outcomes:

- A shared R&I framework for European partners to co-construct new geomodelling solutions.
- An open-source toolbox for 3D geomodelling, to choose the most appropriate solution depending on the geological and application contexts.

GOAL: A Sustainable European Geoscience Data and Innovation Ecosystem - EGDI-e (DIG)

Data and digitisation are central to European public policies, where open access to trusted data underpins evidence-based decision-making. The INSPIRE Directive¹³ provides the foundational layer for access to harmonised spatial data across Europe. However, progressing from data to actionable intelligence requires more than standardised data access alone. It requires an integrated approach that combines robust data governance following the new Data Governance Act¹⁹, applied geological knowledge, advanced data science, and scalable digital infrastructure to maximise information reuse and the creation of value-added services for informed decision-making.

In this context, the current European Geological Data Infrastructure (EGDI) plans to evolve towards a European Geoscience Data and Innovation Ecosystem (EGDI-e). The EGDI-e combines a federated Geological Dataspace, a joint development environment, and a network of geoscience experts collaborating through active communities of practice. This evolution builds on the strengths of National Geological Survey Organisations (NGSOs) combining decades of experience in developing efficient, transparent workflows that integrate geological data, information, and knowledge with research and innovation.

Data is exposed through the federated dataspace under agreed governance rules, while remaining physically and operationally under the control of the NGSOs, thereby safeguarding national ownership and responsibility. The governance framework of the dataspace defines participation rules, sharing agreements, access conditions, and usage limitations, ensuring trust, sovereignty, and controlled data sharing across the ecosystem. Building on this governed foundation, EGDI-e extends beyond data access to support the joint development, deployment, and reuse of models, workflows, and (AI-)tools across NGSOs. The innovation platform itself follows a federated model, allowing participating organisations to retain control over how and where collaboration takes place, while benefiting from shared capabilities.

This transformation enables the creation of dynamic, AI-enabled value chains, where data is continuously transformed into actionable insights and decision-support products. These products integrate geological knowledge, data, and modelling capabilities to support policy development, investment decisions, and resource management. Critically, they are not static outputs but continuously updated through automated pipelines as new data becomes available, ensuring timeliness and relevance.

To support this transition, trusted data governance becomes a critical enabler. The GSE will establish frameworks for AI-ready data, model-aware metadata, and full data-to-model lineage, ensuring transparency, reproducibility, and compliance with European regulations such as the EU AI Act²⁰. Governance structures, including operational and editorial bodies, will ensure quality assurance, standardisation, and coordinated evolution of shared components across the federation.

NGSOs bring extensive expertise in integrating data, knowledge, and scientific workflows. However, enabling full participation in a federated innovation ecosystem requires alignment on data readiness, FAIR implementation, and AI capabilities. The GSE will therefore support capacity building across NGSOs, providing shared tools, guidance, competency frameworks, and training to ensure all participants can contribute to and benefit from the ecosystem.

To realise the EGDl-e, the current EGDl must evolve:

- From infrastructure to ecosystem, by integrating people, organisations, data, models, and technology into a coordinated framework.
- From data to intelligence, by embedding subsurface intelligence generation and decision-support services into the core of EGDl.
- From manual curation to agentic operational efficiency, by deploying shared, human-supervised workflows that reduce administrative bottlenecks across NGSOs.
- From periodically updated to fully dynamic systems, by implementing AI-driven automation and continuously updated value chains.

These transformations are operationalised through four interlinked priorities that together form a continuous value chain. Trusted Data Governance establishes the federated foundation by ensuring that geoscientific data, models, and workflows are FAIR, and AI-ready under a shared governance framework while remaining under national control. Building on this, the Joint Development Environment brings together data, expertise, and technology in collaborative communities of practice, enabling the co-creation and reuse of AI models, workflows, and tools across National Geological Survey Organisations. These shared capabilities are then deployed in Dynamic Intelligence Services, where automated, AI-enabled pipelines continuously transform distributed data into up-to-date insights, predictive capabilities, and decision-support products. Through EGDl-e as a Knowledge Hub also in line with the Interoperability Act²¹ and the AI Act, these data, models, and intelligence services are made accessible via interoperable interfaces, APIs, and knowledge-driven discovery mechanisms, embedding geoscientific intelligence within the wider European digital landscape. Together, these priorities form a federated, continuously evolving value chain in which data, knowledge, and innovation are jointly developed, operationalised, and reused, creating a self-reinforcing ecosystem of trusted, dynamic, and actionable subsurface intelligence.



Figure 8: The European Geological Data Infrastructure lays a foundation for delivering on these UN SDGs.

Priority DIG1 – Trusted Data Governance

A robust and trusted governance framework is essential to support the federated dataspace and innovation platform. Building on INSPIRE, this framework must evolve towards a common semantic foundation for data, models, and agentic AI workflows, enabling interoperability and reuse across the full value chain.

A standardisation framework for geological data collection, interpretation, and dissemination is essential to guarantee interoperability and usability. INSPIRE provides the baseline, extended through harmonised data models and ontologies enabling semantically rich and “High Value” datasets. AI

readiness will be ensured through AI-ready metadata, data model, machine-learning-compatible formats, supporting advanced analytics and automated processing. A Standardisation Framework will define FAIR-compliant shared vocabularies, metadata, dataset and data-sharing protocols (such as the Model Context Protocol - MCP), aligned with scientific, technological, and regulatory requirements, in collaboration with international bodies.

Trust depends on full transparency, continuous quality assurance, and seamless accessibility. The framework will enable end-to-end traceability, documenting data sources, methods, models, actors, and computational processes. Model lineage and AI explainability mechanisms will allow users to trace outputs back to raw data, ensuring reproducibility and accountability. By guaranteeing that data is not only traceable but also rigorously validated for accuracy and easily retrievable without technical barriers, the ecosystem builds a high level of confidence among its users.

Interoperability and broad accessibility will be reinforced through INSPIRE-compliant metadata describing dataset relationships, and linked data and ontologies to represent connections between objects (e.g. boreholes, monitoring stations). Standards such as Observations and Measurements will support process traceability, complemented by dedicated repositories for contextual data.

Governance mechanisms, including PID systems, provenance tracking, quality control with Human-in-the-Loop (HITL) oversight, and compliance with the EU AI Act, will ensure sustainability, auditability, and trust, forming the foundation of a pan-European FAIR and AI-ready geoscientific data ecosystem where high-quality intelligence is openly accessible to users.

Trusted Data Governance

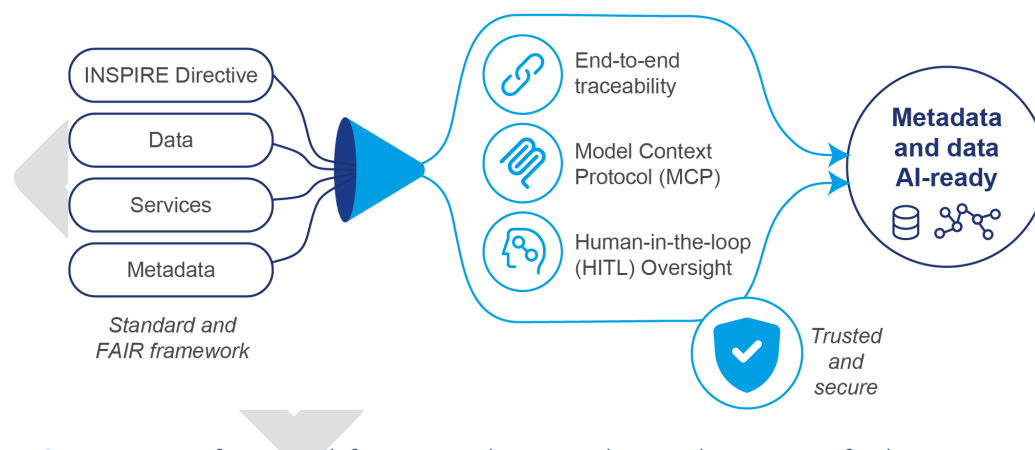


Figure 9: Governance framework for a trusted, FAIR and AI-ready geoscientific data ecosystem.

Action DIG1.1 – Develop trusted governance framework for the European Geological Dataspace, building on INSPIRE and FAIR principles

Expected outcomes:

- Establish robust governance and compliance frameworks by defining onboarding pathways for NGOs, implementing PID systems, and ensuring strict alignment with the EU AI Act, Data Governance Act and INSPIRE Directive to secure a trusted, sustainable dataspace.

- Harmonise standards and ensure FAIR interoperability through unified data models, ontologies, and data-sharing protocols that build a semantically consistent and highly accessible pan-European geological ecosystem.

Action DIG1.2 – Implement automated data quality and governance mechanisms, including metadata validation, quality scoring, provenance tracking, end-to-end traceability, model lineage, and human-in-the-loop (HITL) oversight.

Expected outcomes:

- Deploy automated quality assurance and validation pipelines featuring metadata quality scoring to continuously monitor, measure, and improve the reliability and usability of geoscientific data.
- Drive AI readiness and advanced analytical capabilities by structuring datasets with machine-learning-compatible formats, AI-compatible metadata, and standardised data labelling.
- Guarantee end-to-end traceability and workflow accountability through comprehensive provenance tracking, model lineage, AI explainability mechanisms, and Human-in-the-Loop (HITL) oversight.

Priority DIG2 – Joint Development Environment

A shared computer/model co-development environment to build an AI model repository with benchmark datasets; governance model for shared component reuse in order to accelerate on AI valorisation.

AI and data-driven methods are rapidly maturing, offering unprecedented opportunities for automated document processing, map extraction, semantic search, and intelligence generation. These technologies have the potential to dramatically accelerate our existing workflows and unlock new forms of subsurface and geoscience intelligence.

The Joint development environment is a collaborative environment where people, organisations, data, and technology come together to co-develop the next generation of AI infused geoscientific intelligence equipped with specialised domain-specific automated services (agent skills). By developing AI models (including energy-efficient Small Language Models), agentic tools, workflows, and data processes together, Europe's geological surveys can maximise their collective capabilities by co-creating reusable components. This collaborative approach accelerates delivery, optimises resources, and enables robust shared testing and validation.

It will provide governed access to curated benchmark datasets and an AI model repository, enabling member organisations to build on shared components.

By using standardised metadata, aligned vocabularies, shared ontologies, and consistent processing workflows as input coherent interpretation of geoscientific information is made possible, generating enriched or harmonised versions of these same resources as output. It creates a reinforcing cycle of continuous semantic improvement across the European geological knowledge ecosystem.

At the same time, the joint development environment and the connection to the EU Geological Dataspace safeguards Europe's strategic autonomy in subsurface intelligence.

Action DIG2.1 – Develop a collaborative environment within European Geological surveys

Expected outcomes:

- Foster pan-European co-development and strategic collaboration by establishing a long-term shared environment among National Geological Survey Organisations (NGSOs) and EU programmes like EOSC to co-create next-generation, AI-infused geoscientific intelligence.
- Operationalise robust AI lifecycles and testing sandboxes by implementing end-to-end pipelines from prototype to production, incorporating Human-in-the-Loop (HITL) validation mechanisms to ensure reliable and high-performance workflows.
- Maximise asset reuse and development efficiency through the certification, versioning, and tracking of reusable components, effectively reducing development costs and preventing the duplication of efforts across countries.

Action DIG2.2 – Promote sustainable AI solutions and advanced capacity building in a secure Infrastructure

Expected outcomes:

- Establish a secure, compliant repository infrastructure that provides governed access to curated benchmark training datasets and AI models, strictly aligned with the EU AI Act and clear cross-border data-sharing rules.
- Promote sustainable AI solutions and advanced capacity building by prioritising energy-efficient, low-latency models with active consumption monitoring, while simultaneously delivering advanced cross-country collaborative training programmes.

Priority DIG3 – Dynamic Intelligence Services

To build an ecosystem landscape for automated updating, AI pipelines & transparent value chains sharing a compute infrastructure and streaming from national monitoring networks

To transition from periodically updated datasets to continuous, real-time knowledge systems, this action develops Dynamic Intelligence Services based on AI-driven pipelines, multi-agent orchestration, automated updating, and continuous data flows. It will implement end-to-end ingestion-to-insight workflows, enabling automated data collection, processing, integration, and insight generation. Continuous AI model updating frameworks will ensure that models evolve with incoming data, while the integration of real-time streams from national and European monitoring networks will provide up-to-date situational awareness. These capabilities will be supported by a shared European computing infrastructure, enabling scalable analytics, simulation, and predictive modelling.

Transparency, data sovereignty, and continuous quality assurance will extend across the full value chain, including models, training datasets, versions, and workflows. Connections between datasets (e.g. databases, maps, 3D models) will rely on high-quality INSPIRE and FAIR metadata to guarantee seamless accessibility, while relationships between objects (e.g. boreholes, monitoring stations) will be captured through linked data, ontologies, and relational systems. Structured metadata and provenance frameworks will document how insights are generated, enabling users to trace results back to underlying data and processing steps. This ensures reproducibility, explainability, operational security, and trust in AI-enabled processes.

Action DIG3.1 – Develop Dynamic Intelligence Services based on AI-driven pipelines, automated updating, and continuous data flows

Expected outcomes:

- Deploy advanced predictive and early-warning services designed for proactive risk detection, such as hazard assessment and resource depletion, tailored to the specific needs of defined priority user groups.
- Orchestrate multi-agent AI architectures with rigorous oversight by integrating complex analysis workflows with Human-in-the-Loop (HITL) supervision to establish validation and human oversight mechanisms (anti-hallucination), ensuring transparency and accountability across the entire value chain.

Action DIG3.2 – Build Federated AI Infrastructure and Real-Time Data Pipelines

Expected outcomes:

- Implement automated end-to-end workflows that enable seamless ingestion-to-insight pipelines, transforming real-time data streams from national and European networks into dynamic, continuously updated knowledge systems.
- Establish a federated European AI-Factory infrastructure strategy to deliver scalable computing, simulation, and continuous model updating capabilities through a balanced, strategic approach to reusing, building, or hybridising technical resources.

Priority DIG4 – EGDI-e as knowledge hub in the EU digital landscape

Positions EGDI-e as a European Geoscience Dataspace Node that exposes data, models, and services through open APIs, knowledge graphs, and interoperable links to INSPIRE, Copernicus, EPOS, EEA, and EOSC.

EGDI-e will be fully integrated within the European digital landscape. In this role, it supports not only access to data, but also to the co-created models, workflows, and intelligence services.

In this role, EGDI-e will act as a European Geoscience Dataspace Node, ensuring interoperability and connectivity with key European frameworks. This includes alignment with INSPIRE, integration with Copernicus services, and active interconnection with emerging environmental, economic, and social dataspace, enabling cross-domain data fusion and multidisciplinary insights.

Core enabling technologies will include semantic search, knowledge graphs, and natural language interfaces, allowing users to discover, access, and interact with complex geoscientific information in an intuitive and context-aware manner. These capabilities will transform fragmented datasets into connected knowledge assets, accessible across disciplines and user communities.

The development of an open API infrastructure will support standardised, secure, and scalable access to data and services, fostering reuse, innovation, and the development of value-added applications across sectors. Through open access principles and interoperable standards, EGDI-e will strengthen Europe's digital landscape and data sovereignty.

By positioning itself as a connector between geoscience and other scientific and policy domains, EGDl-e will enable a federated and collaborative knowledge environment, supporting research, industry, and public authorities in addressing complex societal and environmental challenges at European scale.

Action DIG4.1 – Establish EGDl-e as a European Geoscience Dataspace

Expected outcomes:

- Establish EGDl-e as the premier European geoscience hub by securing its position as a fully integrated reference node within the wider European digital and dataspace ecosystem, supported by formal partnerships across policy, industry, and research.
- Implement cross-domain technical and governance interoperability through formal agreements and live data connectors with key European initiatives—including EPOS, Copernicus, EEA, and EOSC—enabling seamless resource discovery and reuse.

Action DIG4.2 – Interoperability mechanisms with other communities

Expected outcomes:

- Transform fragmented datasets into interconnected knowledge assets by deploying advanced knowledge graphs, linked data technologies, and natural language interfaces to facilitate intuitive, cross-disciplinary discovery and navigation.
- Develop a mature, standards-based API ecosystem that provides secure, scalable, and machine-actionable access to geoscientific resources, driving the creation of innovative third-party applications, reference tools, and decision-support services.

Economic and Environmental Geoscientific Focus

GOAL: Energy Transition & Decarbonisation (ETD)

European and national legislation, policy roadmaps, and research initiatives focus on enabling and accelerating the development and upscaling of new sustainable geo-energy and carbon emission reduction technologies that can be deployed in both the shallow and deep subsurface. To this end, stakeholders in governmental and non-governmental organisations and industry require fit-for-purpose geoscientific data, information, and decision-support criteria for performing techno-economic evaluation of geo-energy resources, de-risking investments, planning and permitting new sites for deployment, regulating operations, and managing environmental impacts. Optimising use of the subsurface can support maintaining and creating jobs and industrial manufacturing in Europe, while enabling a sustainable future and supporting climate goals.

Overview of recent steering policies and legal frameworks

The following policy documents and legal frameworks provide guidance to the formulation of the Strategic Research and Innovation Agenda for Goal 3 on Energy transition and decarbonisation:

1. European climate neutrality, competitiveness and resilience

The European Climate Law²² is the legally binding framework that commits the European Union to achieving climate neutrality by 2050. It establishes intermediate targets of a 55% reduction in net greenhouse gas emissions by 2030, and an ambitious 90% reduction target by 2040, both compared to 1990 levels.

The Draghi report on “The Future of European Competitiveness”²³ explains how Europe can afford and realise the transition to net-zero. It considers a range of renewable technologies (including green hydrogen, geothermal, nuclear) as strategic options to boost Europe’s industrial competitiveness, while Carbon Capture Storage and Use (CCS/CCU) are identified as essential solutions where (full) electrification is not feasible (e.g. some energy-intensive and hard-to-abate industries such as cement).

The 2020 Strategic Foresight Report²⁴ puts forward resilience as a new compass for EU policies. Ultimately, it urges to shift towards a paradigm of a more sustainable growth and societal development path. In this context, Europe needs to further strengthen its resilience, to be able to be more prepared for future shocks and to emerge stronger by intensifying the transitions.

2. Decarbonisation and Carbon Capture & Storage

Under the framework of the Green Deal, the Industrial Carbon Management Strategy highlights technologies to store and use CO₂. In this framework, the Clean Industrial Deal acts as an overarching, strategic business and policy roadmap to make decarbonisation profitable, while the NZIA serves as the legally binding regulation to implement decarbonisation. NZIA incorporates specific targets for reaching an annual CO₂ injection capacity of ≥50m tonnes CO₂ by 2030 (Article 20). In addition, it sets requirements for Member States to submit annual reports on CO₂ storage capacity data empowering stakeholders to monitor and assess progress toward the Union-wide CO₂ injection capacity target (Article 21) and places an obligation on oil and gas producers to contribute to the Union’s CO₂ injection capacity objective by 2030, positioning them as key developers in advancing the EU’s carbon storage industry (Article 23).

Complementary to above legislative frameworks, the EU CCS Directive establishes a comprehensive legal framework for the environmentally safe geological storage of CO₂. It covers the entire lifecycle of storage sites, dictating rules for site selection, permitting, operational monitoring, closure, and the transfer of responsibility back to the state.

3. Renewable energy, energy independence and geothermal energy

The Renewable Energy Directive RED II and its 2023 revision (RED III) set the overarching, legally binding targets to increase the share of renewables in the EU's energy mix to >32% of total final energy consumption by 2030, while encouraging the integration of renewable energy sources in buildings. The European Parliament Resolution on geothermal energy acts as a specific catalyst, urging the European Commission to transform RED's broad renewable goals into targeted action for the geothermal sector, explicitly pointing to geothermal energy as the vital solution for localising baseload power and district heating networks.

The EU's recent AccelerateEU Communication promotes geothermal energy as part of its strategy with an objective to reach 250 GW of installed geothermal capacity by 2040 by minimizing the current barriers to its development (among others high exploration costs and financial risks linked to geological uncertainties). The Commission will support Member States and stakeholders in gathering detailed geological data and create an EU-level database. The recently adopted EU Electrification Action Plan²⁵ further strengthens this policy direction by recognising geothermal energy as a key enabler of electrification, highlighting its potential for high-efficiency renewable electricity generation as well as renewable heating and cooling with reduced network costs, provided that an enabling framework is established.

4. Adopting hydrogen as key component of EU's energy transition strategy

The EU Strategy on Hydrogen put forward a vision for the creation of a European hydrogen ecosystem aligned with the European Green Deal, with ambitious hydrogen production and imports (2 x 10 Mtonnes) by 2030. In this context, underground hydrogen storage can be a key factor to support European energy system decarbonisation and facilitate development of a fully integrated clean hydrogen ecosystem. The development of underground hydrogen storage across Europe depends on geological conditions and availability of storage sites, as well as (local) storage needs. Currently, planned hydrogen storage projects are insufficient to cover predicted demand. The SRIA for the Clean Hydrogen Partnership mentions specific priorities relating to the expertise and research activities supporting deployment and upscaling of underground hydrogen storage.

A major part of EU's decarbonisation and energy transition will happen within the subsurface

In summary, the requirements and ambitions in key European strategies and legislations identify a need to characterise investible potential for production of deep and shallow geothermal energy, storage of heat and cold, permanent storage of CO₂, and temporary underground storage of hydrogen and other storable energy carriers, considering local impacts and safety towards national to EU security and system-wide benefits.

EuroGeoSurveys has already taken major steps in delivering available subsurface information and knowledge via the GSEU project and will further support the growth of a net-zero energy industry by delivering the following R&I priorities and actions.

The Draghi Report emphasises the need for increased levels of coordination across the multiple policies impacting the EU's targets and ambitions on e.g. energy, climate, environment, trade, circularity, and growth. As all these policy areas have relations to geology, their alignment relies on open access to reliable, harmonised, and interoperable geological data

The overarching expected outcomes for the R&I actions in this goal are directed at:

- Enabling the implementation of subsurface data, information, and knowledge in national and European policy and decision-making processes.
- Establishing future-proof information platforms that serve expert and non-expert needs and allow continuous renewal and incorporation of new data and models, with innovative methods including AI-based tools.
- Investigating and leveraging new prospects that support Green Deal ambitions.



Figure 10: Our Energy Transition & Decarbonisation actions contribute to delivering on these UN SDGs.

Priority ETD1 – Develop and deploy pan-European information and decision support systems to accelerate deployment of geothermal systems

Geothermal is a proven and versatile renewable energy resource with vast untapped potential for dispatchable low-emissions electricity generation, heating and cooling of residential and commercial buildings, industrial processes, and agriculture. Geothermal has been a part of energy systems for more than a century but has played a limited role globally. Recent European initiatives urge its enhanced use given its increasing role in a clean energy transition. This priority specifically addresses the objectives set out in the EU geothermal strategy proposal and the AccelerateEU Communication, is fully consistent with the more recent EU Electrification Action Plan, and complements the R&D priorities of the ETIP-Geothermal SRIA:

- Fit-for-purpose digital geological data for techno-economic evaluations of geothermal resources, de-risking schemes, and efficient permitting and development of geothermal projects.
- Accelerating underground thermal energy storage.
- Improved environmental performance assessment for different use perspectives.

The expected outcome of this priority is to ensure that pan-European geothermal information systems are tailored to support and implement European policies on sustainable energy use of the subsurface, ensuring efficient and informed decision-making. Depending on the geological context and EU country, this priority covers either deep geothermal energy, shallow geothermal energy, or both.

Directive (“RED III”)



NGSO actions for policy implementation

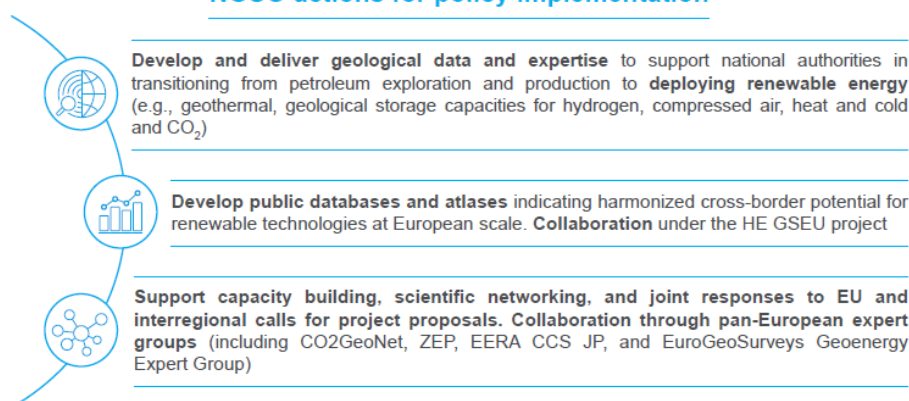


Figure 11: Key geological information services related to the Renewable Energy Directive (III)^{26,27}.

Action ETD1.1 – Accelerate techno-economic geothermal development

Expected outcomes:

- A **European Geothermal Investment Atlas** enabling the de-risking of geothermal projects by supporting project-level technical assessments and national de-risking guarantee schemes through detailed investigations of geological uncertainties, improved understanding of pre-drilling geological risks, and guidance on addressing information and exploration gaps. This includes site maturity frameworks, geothermal resource readiness indicators, exploration maturity scoring, and risk-screening tools for developers and financiers.
- **Advanced pan-European geothermal data discovery and access tools**, to improve the discoverability, accessibility, and usability of geothermal data, information, and knowledge generated through past, ongoing and future national and European research projects, exploration and monitoring campaigns, and relevant industry repositories. Contribute to the implementation of geothermal data transparency regulations.

- **Multi-scale Geothermal Intelligence Services** complementing pan-European scale screening information on state-of-play with higher-resolution local and regional datasets. This includes dedicated information on the heterogeneity and quality of data per region, providing guidance for disclosing and revealing geothermal potential in under-explored and under-developed regions and enabling practical project development workflows.
- **State-of-the-art geothermal modelling and assessment platforms** delivering an extended geothermal resource base and identifying untapped geothermal potential across Europe through the application of advanced resource assessment methodologies, play-based portfolio analysis, and Artificial Intelligence (AI) and Machine Learning (ML) techniques. This will incorporate assessments of the Probability of Success (PoS) for geothermal projects from both engineering and a Levelised Cost of Energy (LCOE) perspectives.
- Increased **understanding of the risks and benefits associated with geothermal energy** for society, European and national strategic interests, and Sustainable Development Goals (SDGs)²⁸. This includes the assessment of the role and value of geothermal energy in European energy transition scenarios, as well as environmental performance and risk assessments to enhance the sustainability and efficiency of geothermal projects.

Action ETD1.2 – Develop tailored information services for all stakeholders and the public.

The preparation of tailored information for the public, local authorities, governmental organisations and other stakeholders is key to supporting integrated decision procedures between all phases of development, adequate communication between different elements of the value chain and alignment of interests between different regulatory domains involved in geothermal permitting and deployment.

Expected outcomes:

- Establish **structured collaboration** with European institutional actors, official national geological information providers, modelling communities, and complementary information providers to avoid duplication and strengthen European interoperability.
- Develop **dashboards** translating technical information to meet the needs of specific target groups

Priority ETD2 – Establish pan-European data, information, and knowledge for the accelerated and secure deployment of CO₂ underground storage potential in both core development areas and emerging R&I areas

In Europe, Carbon Capture and Storage (CCS) is developing heterogeneously. Some countries have projects in advanced stages of permitting and financial investment decisions, while others have a far less mature view of storage opportunities. Extensive collection of primary data and analysis of raw data are still required. As the European CCS industry transforms from isolated flagship demonstration projects to a pan-European industry, requiring the development of hundreds of storage sites, there is an urgent need to optimise use of the subsurface.

The CO₂ geological storage atlas of Europe, being developed through the GSEU project, has collated available data for a harmonised pan-European view and uses Storage Readiness Levels to highlight the

maturity of storage site development. The CO2SITE project will further develop the atlas, providing additional data to support investment decisions on storage. Through NZIA, data on potential storage sites and CCS projects will be released. The need remains for significant resources to analyse data and undertake fundamental research to support delivery of tools that can inform decision makers. There also is the need for R&I to tackle questions raised by the developing fleet of CO₂ storage projects in Europe.

European Climate Law & Net Zero Industry Act

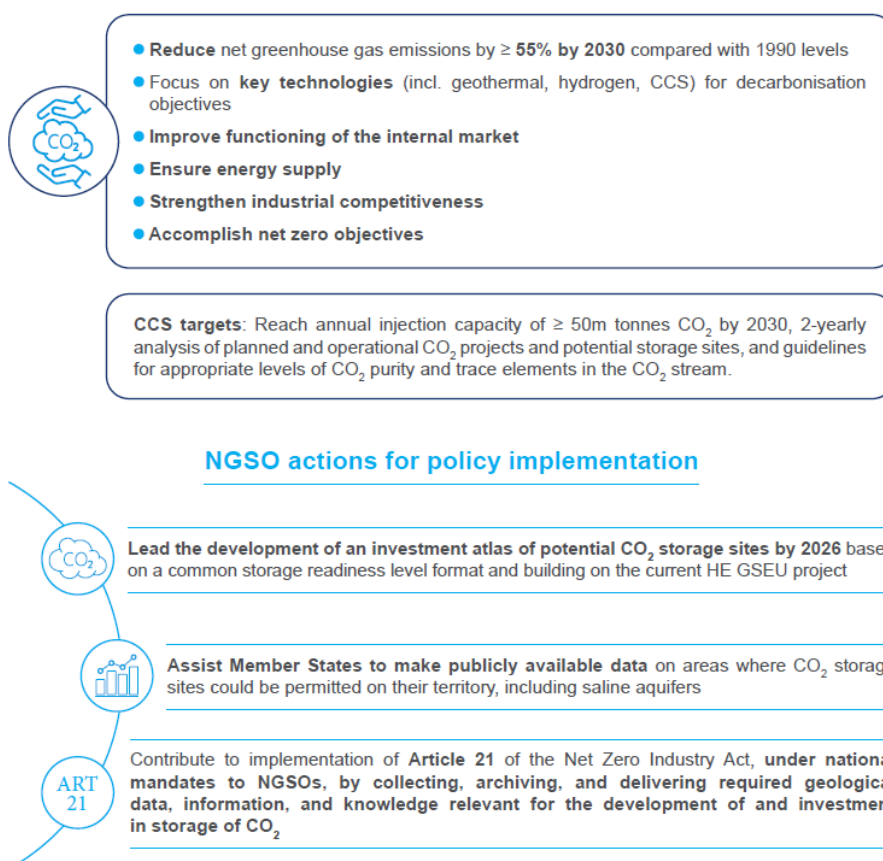


Figure 12: Key geological information services related to the European Climate Law and Net-Zero Industry Act.

In line with targets in the Green Deal, Industrial Carbon Management Strategy²⁹, the NZIA, and the EU Communication on ‘A Green Deal Industrial Plan for the Net-Zero age’, the main expected outcomes of this priority are to:

- Accelerate the secure and efficient deployment of underground CO₂ storage in Europe.
- Directly contribute to enabling use of information released under the Net-Zero Industry Act to create a pan-European CO₂ storage opportunities portfolio and produce a pan-European investible storage assessment.
- Facilitate and improve knowledge sharing between stakeholders to accelerate and optimise deployment of CCS. This includes the CCS knowledge-sharing platform highlighted in the

Communication on Industrial Carbon Management that will facilitate the collection of information on and sharing of best practices between CCS projects in the EU. Contribute practical knowledge on CO₂ storage e.g. through the European Carbon Dioxide Capture and Storage Laboratory Infrastructure facilities.

Action ETD2.1 – Contribute to closing remaining knowledge gaps through R&I and by responding to new research challenges identified by storage projects that will come online over the next few years

Expected outcomes:

- **Map and parameterise saline aquifers** as important targets of onshore and offshore CO₂ storage at national and pan-European scale.
- Technical recommendations for **characterising and implementing a pan-European CO₂ storage network**, including optimising use of pressure budget (including regional and cross-border), transboundary issues, and site closure and abandonment. Improve understanding of potential migration pathways to inform risk assessment.
- Technical information to **support national discussion and harmonised decision-making** for national and European research programmes and development of CCS strategies. Continue to demonstrate the value of geoscientific knowledge to achieving net zero. Assess priority actions to enable assessment of investable storage, including identifying promising geographical areas to prioritise data processing, areas where new data are required, regulatory issues, etc. Share knowledge on innovative local storage solutions (e.g., geothermal with CO₂ and mineralisation storage).
- Co-developed **joint research in areas of common interest to NGSOs**, delivering European and national opportunities for CCS. Advance innovative monitoring technologies including cost/benefit. Investigate innovative local storage solutions and niche opportunities such as CO₂ sequestration in basalts.
- Up-to-date information systems providing **early access to fit-for-purpose CO₂ storage-relevant data** by implementing innovative solutions for processing, ingesting, and analysing large quantities of (industry/legacy) data for CO₂ assessments (e.g., ML). Improved means to share knowledge to maximise use of data released under the Net-Zero Industry Act. Share experience on value of reprocessing data with current approaches.
- **Minimum requirements for storage site monitoring and modelling for operator and stakeholder assurance**, including use of on-site and remote-sensing techniques for monitoring of ground CO₂ and ground movement during all phases of a project, from obtaining natural background trends to post-site-closure monitoring. Advance understanding of near-wellbore processes.

Priority ETD3 – Enable secure, efficient, and timely unlocking of underground hydrogen storage capacities

The EU Strategy on Hydrogen³⁰ put forward a vision for the creation of a European hydrogen ecosystem aligned with the European Green Deal, with ambitious hydrogen production and imports (2 x 10 Mtonnes) for 2030. In this context, underground hydrogen storage can be a key factor to support European energy system decarbonisation and facilitate development of a fully integrated clean hydrogen ecosystem. The development of underground hydrogen storage across Europe depends on geological conditions and availability of storage sites, as well as (local) storage needs. Currently, planned

hydrogen storage projects are insufficient to cover predicted demand. The SRIA for the Clean Hydrogen Partnership (Clean Hydrogen Joint Undertaking) mentions specific priorities relating to the expertise and research activities of NGSOs, including:

- Development of decision support and planning tools to help unlock hydrogen storage as a scalable and flexible solution in the European energy system, underpinned by assessment and demonstration of underground storage to validate the performance in different geology.
- Provision of sustainable and safe designs for underground storage including studies on lined mined caverns for storing hydrogen when neither salt caverns nor porous media are available.
- Development of tailored information to support, accelerate, and de-risk underground hydrogen storage including assessment of effects and impacts that may occur during injection and storage of hydrogen in underground reservoirs.

Action ETD3.1 – Develop fit-for-purpose information services to support and accelerate techno-economic development of underground storage solutions for hydrogen and other energy carriers

Expected outcomes:

- Public state-of-the-art information systems to improve European-level accessibility and implementation of national storage capacity data, information, and knowledge by integrating and unlocking data repositories.
- Accelerated commercialisation and optimised upscaling of underground hydrogen storage projects by collecting, analysing, and disseminating public information and monitoring data from pilot projects and commercial-scale demonstrators across Europe.
- Improved derisking of technical potential at project-level and support of national derisking guarantee schemes through detailed investigations of geological uncertainties, insights into pre-drill geological uncertainties, and guidance on resolving information and exploration gaps.
- Improved environmental performance assessment to enhance project sustainability and efficiency by developing advanced monitoring systems and methodologies and promoting an open data policy for dissemination and reuse.

Priority ETD4 – Maturing next-generation geoenery technologies

There is a wide range of emerging technologies (e.g., deep geothermal closed-loop systems, recovery of critical raw materials (e.g., lithium) from geothermal brines, natural hydrogen) that cannot yet be mapped at pan-European scale. However, these technologies are expected to have potential economic interest and a significant role in achieving decarbonisation goals.

Action ETD4.1. – Facilitate the innovation and deployment of new technologies

Expected outcomes:

- Advanced recovery of CRM from geothermal brines as by-products by delivering tailored information and tools, including resource assessments. This will support implementation of CRM Act and NZIA to maximise potential CRM sourcing and make geothermal power generation more economically favourable.

- Integration of enhanced geothermal systems, advanced geothermal systems, and closed-loop into pan-European geothermal information and decision support systems by investigating their feasibility and contributing to sustainable deployment.
- Insight on the presence of technically and economically exploitable natural hydrogen resources by modelling basins and reservoirs that could accumulate favourable natural hydrogen volumes and developing tools to characterise hydrogen-bearing rocks.
- Improved exploration and exploitation of natural hydrogen resources by developing exploration methodologies with geophysical, new gas monitoring techniques, and possibly remote sensing technologies.

Priority ETD5 – Develop information services to support offshore wind and infrastructures planning and deployment

Offshore wind is a strategic pillar of Europe’s energy security and resilience. The EU currently generates ~3% of its electricity from 22 GW of offshore capacity, with rapid expansion expected: 151 GW of new wind power capacity over 2026-2030 and up to 366 GW by 2050. Supporting such growth, particularly as projects move into deeper water, requires consistent and high-quality geological models to underpin the success of project delivery.

To meet these needs, shallow offshore geological models (up to ~100 m below seabed) must be developed using the growing volume of data from offshore wind projects³¹. In the GSEU project (ending 2027), “optimised offshore wind farm siting” is a proven, working model utilising existing research data from EMODnet Geology and Bathymetry³². Here, key geo-engineering constraints at the seabed and in the subsurface are presented through the development of a user-friendly tool based on the Geo-Assessment Matrix.

This proposal builds on the foundations created during GSEU. The actions proposed will not only support offshore wind, but the wider development of offshore sustainable energy infrastructure for Europe’s energy transition and decarbonisation goals. Additionally, it supports the Geological Service for Europe (GSE) vision of a permanent, pan-European geological knowledge service under the “Geo-Energy & Storage” theme.

- **Data & Information Services:** Offshore wind requires accurate harmonised offshore Quaternary and relevant bedrock stratigraphic frameworks, EMODnet Geology-linked datasets (e.g., bathymetry, seabed habitats and geomorphology), and pan-European hazard layers to derisk site selection;
- **Research:** Offshore wind needs coordinated EU-scale research including sediment mobility, geotechnical behaviour, and a holistic understanding of cross-border basin geological evolution;
- **EU policy support:** Offshore wind development requires advisory capacity for maritime spatial planning, energy corridors, and transboundary coordination – a core part of GSE’s policy pillar. Further, offshore wind development requires operational decision support modules for planning and managing both siting and land connection.

Action ETD5.1 – Develop harmonised, transnational Quaternary stratigraphic framework (Offshore)

Expected outcomes:

- Maintenance and ongoing development of the Geo-Assessment Matrix developed as part of GSEU will ensure a continuously updated evidence base.
- Develop a readily available open access harmonised, pan-European chronostratigraphic framework for geological units of engineering relevance to depths of up to 100 m below the seabed.
- Identify and compare subsurface characteristics across European offshore regions to determine where stratigraphic units share similar geohazards, geotechnical behaviours, or engineering constraints. This will enable the recognition of common geological conditions, support risk-aware planning, and improve the predictability of subsurface challenges for offshore development.

Action ETD5.2 – Develop geospatial data and information to support improved regional characterisation of seabed and subsurface constraints

Expected outcomes:

- Develop new geospatial regional layers for offshore wind farm site and cable route optimisation (sediment mobility and seabed lithology constraint maps), leveraging EMODnet DTM 2024 and national layers based on the Geo-Assessment Matrix developed as part of the GSEU³³.
- Enable faster updates to geological screening maps, aligned with policy and infrastructure needs.
- Develop operational decision support modules for optimised offshore wind farm siting and land connection, building on the recommendations developed in GSEU based on the experiences and needs of GSOs across Europe³⁴.

Action ETD5.3 – Implement FAIR data principles across geological data systems

Expected outcomes:

- Develop a detailed and fully referenced bibliography underpinning the spatial planning guidelines to include geological constraints and siting of turbines.
- Ensure geological data are findable, accessible, interoperable and reusable (FAIR) ensuring seamless integration and consistent use across national and project boundaries.
- Reduction in duplicated effort through coordinated data standards and shared digital infrastructure, enabling more efficient use of national geological survey resources and preventing repeated acquisition of equivalent datasets.
- Increased uptake of geological datasets in research, development planning and policy.

GOAL: Responsible Raw Materials (RRM)

Raw materials are essential to Europe's economic competitiveness and security, particularly in the context of the energy and digital transitions, but also with a view to improving its sovereignty and defence. Europe's heavy dependence on imports of raw materials and intermediate products from third countries³⁵ has weakened value chains in, amongst others, electronics, automotive and aerospace, construction, and battery production. This dependence risks not only sovereignty and industrial opportunities but also transfers the environmental and social costs of European consumption to other regions. This ethical dimension underlines the need to adopt responsible sourcing practices throughout the supply chain.

New strategic drivers appeared to strengthen national safety and EU's independence from outside markets in raw material supply and production. This applies especially to strategic metals and supply-sensitive raw materials. The use of raw materials for military applications, or energy metals (e.g., U, Th) should also be addressed in the upcoming R&I priorities. At the end of 2025, the European Commission proposed a targeted revision of the CRM Act aimed at strengthening the Union's security of supply in response to growing geopolitical tensions, specifically to enhance the resilience of defence- and aerospace-related value chains. The focus is no longer only on critical raw materials but also on strategic materials.

Most European countries are developing or updating National Exploration Programmes (NEPs) in response to the Critical Raw Materials Act (CRM Act). These programmes are either already underway or about to be launched. They will generate a substantial amount of new geological data on Europe's metallogenic potential. A significant effort will be required to analyse, harmonise, and integrate these datasets at the European scale. At the same time, this unprecedented body of information will create new opportunities for research and innovation (R&I), particularly in the fields of mineral systems understanding, predictive exploration, data integration, and resource assessment.

In addition to critical and strategic raw materials, the continuously expanding building and construction sector is also driving a growing demand for aggregates. Ensuring access to and the sustainable exploitation of these construction materials under environmentally responsible conditions has become a major territorial and environmental challenge. It may generate competing uses of the subsurface and requires a comprehensive understanding of geological resources and material properties. The extraction of marine aggregates also represents an important challenge for coastal safety and coastal protection in the EU. Large volumes of marine aggregates are currently used, or planned for use, to reduce coastal erosion, flooding, storm surges, and the impacts of climate change, including sea-level rise. This increasing demand is placing significant pressure on available onshore and offshore resources and highlights the need for a Europe-wide assessment, strategic planning, and sustainable management of aggregate resources.

European Critical Raw Materials Act



- **Ensure a secure and sustainable supply of CRM** strengthening European CRM value chains
- **Diversify CRM imports** to reduce strategic dependencies
- **Improve capacity to monitor and mitigate risks of disruption** to CRM supply
- **Improve CRM circularity and sustainability**

NGSO actions for policy implementation

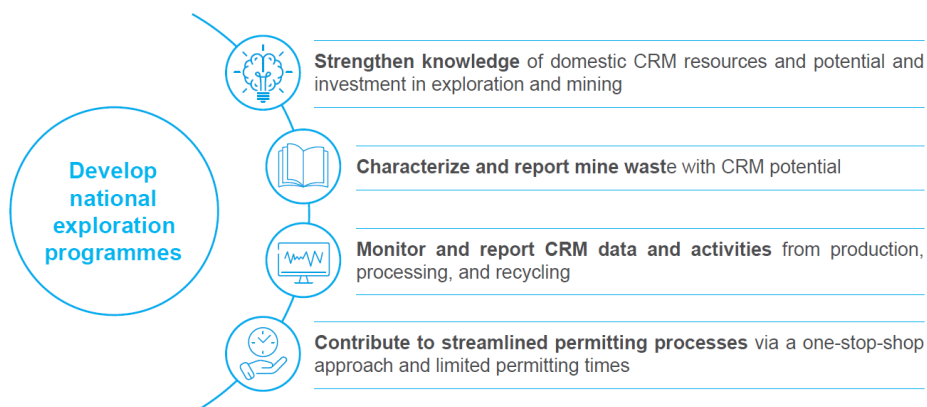


Figure 13: Key geological information services related to the Critical Raw Materials Act.

The CRM Act⁵, in its ambition to ensure secure and sustainable supplies of CRM for Europe, will draw on the expertise, research and innovation of EuroGeoSurveys and its member NGSOs to deliver:

- Resource assessments including national exploration programmes (NEPs) to identify additional national resources and potential (primary and secondary).
- Raw materials data compiled and harmonised at European scale, onshore and offshore, primary and secondary, including supporting deployment of UNFC and promotion of the UN Resource Management System.
- Standardisation including common methods and best practices, particularly targeting transboundary regions.
- Public knowledge and awareness. The future of the European raw materials sector depends on public understanding, education, and support.
- Raised capacity and contributions to international dialogue with partner organisations or third countries to share best practices and expertise on raw materials supply chains, contributing to raw materials diplomacy, diversification of sourcing, and strategic partnerships.

EuroGeoSurveys will support the European raw materials policy and industry in assessing Europe's raw materials potential, developing innovative and sustainable solutions for exploration, characterisation, production, and recycling.

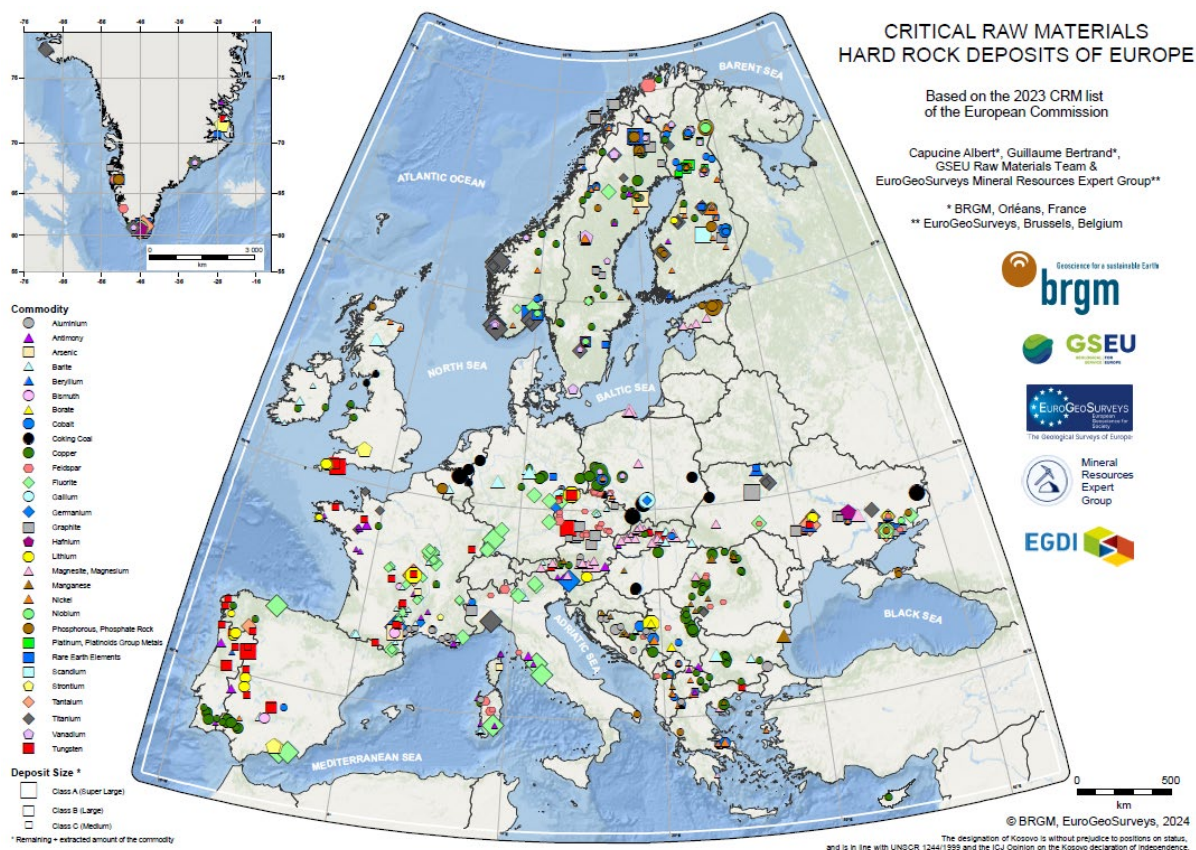


Figure 14: Map of Critical Raw Materials hard rock deposits of Europe (GSEU, 2024).

CRITICAL RAW MATERIALS OFFSHORE OCCURRENCES AND DEPOSITS OF EUROPE

Based on the 2023 CRM list of the European Commission

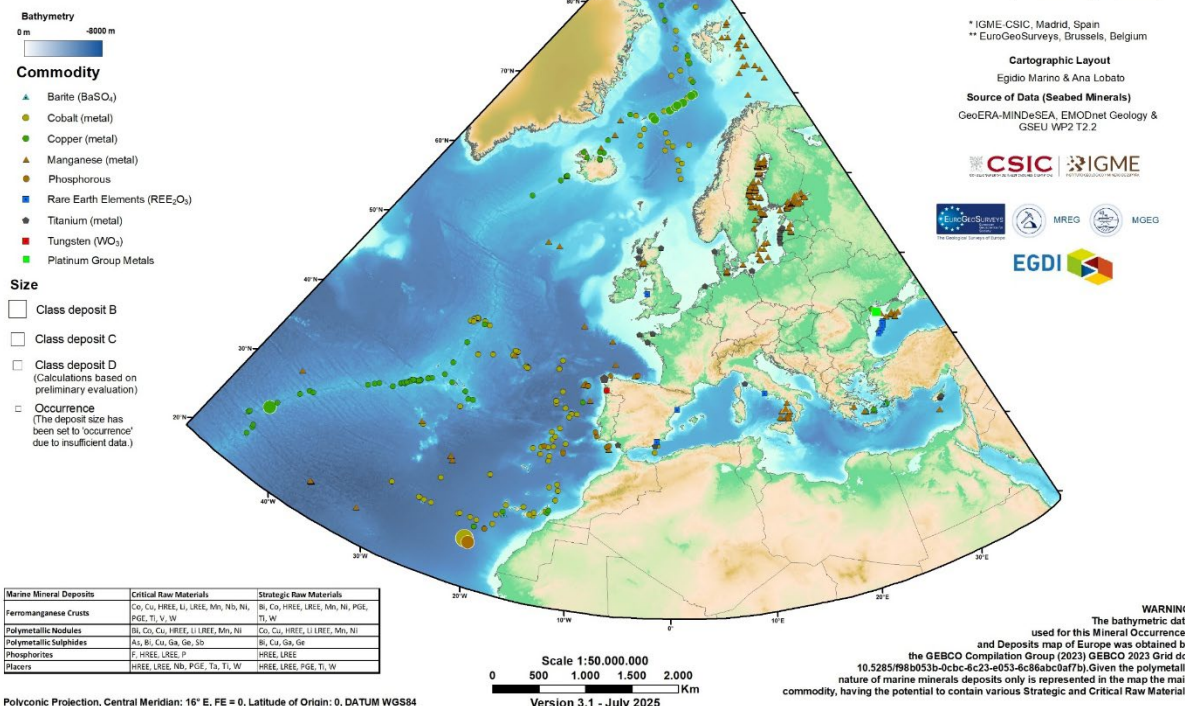


Figure 15: Critical Raw Materials Offshore Occurrences and Deposits in Europe (GSEU, 2025).



Figure 16: EuroGeoSurveys Responsible Raw Materials actions contribute to delivering on these UN SDGs.

Priority RRM1 – Support raw materials exploration to assess European potential

The CRM Act advocates a more global approach to securing CRM in Europe. The European NGOs will be key players in the development of regional mineral exploration methods and programmes. Although Europe has developed substantial knowledge of its raw materials potential through its long mining history, there undoubtedly remain significant discoveries to be made, particularly of metallic deposits. Exploration for deeper, unconventional mineral deposits requires development of new metallogenic models based on comprehensive reconstructions of the geological history, reassessments of existing data using new geological concepts, and in-depth analyses of mineral systems. This involves analysing and reassessing all of Europe's geological potential using centralised, standardised data. To achieve this, NGOs and AI data infrastructure experts must work together through strong and active networks. The link with data science and AI should be strengthened. AI is bringing breakthrough opportunities to harmonise data and to process/valorise data to produce added-value knowledge (in particular legacy data). Based on these considerations, EuroGeoSurveys has identified the following actions:

Action RRM1.1 – Maintain a reliable and harmonised inventory of European mineral resources, accessible to multiple stakeholders

Expected outcomes:

- Further develop, maintain, and regularly update the MIN4EU database under the umbrella of the EGDI, to deliver regularly updated access to harmonised, complete, and verified mineral resource data, in line with common European standards. This includes harmonisation of resource data using the UNFC and INSPIRE standards.
- Regular delivery of new, improved data, information, and knowledge of European mineral resources.
- Data packages, analyses, and explanatory products customised to different stakeholders, to maximise dissemination, awareness, and understanding of Europe's onshore and offshore mineral resources.

Action RRM1.2 – Apply cutting-edge exploration models that integrate mapping, tectonics, mineral systems analysis, and advanced data processing techniques

Expected outcomes:

- A harmonised database of lithotectonic units of all mineral provinces in the European territory coupled with data on geochemical and geophysical characteristics. This data will be upgraded especially in connection to the national exploration programmes, based on detailed

characterisation of European lithotectonic units, encompassing aspects of their geological history and mineral prospectivity. This will provide a basis for renewed assessment of mineral raw materials potential, and application to other resources such as CO₂ storage, groundwater, geothermal energy and to geohazard risk assessment and mitigation.

- Collaborative research initiatives between NGSOs and academia targeting specific European mineral provinces to re-examine ore-forming processes in key areas (e.g., the Fennoscandian Shield, Kupferschiefer, Variscan, and Alpine belts). This will contribute to deciphering complex ore-forming processes, essential to develop appropriate exploration strategies.
- A comprehensive assessment of European ore deposit areas supported by Machine Learning (ML) approaches, contributing to reassessments of mineral provinces, and requiring consistent and standardised description of lithological and geological units to generate favourability maps of mineralisation occurrence. Such maps, hosted by EGDI, will enable targeted exploration of favourable regions.
- 3D predictive modelling approaches, in parallel with better knowledge of geological structures and geometries at depth, to support exploration for deep and under-cover deposits.

Action RRM1.3 – Spearhead collaborative R&I initiatives with industry and technology partners, to improve exploration methods from European to local scale

Expected outcomes:

- Advanced exploration technologies including innovative geophysical surveying, 3D surveys, and multidisciplinary approaches incorporating geological mapping, geochemistry, drilling, core analysis, petrophysical studies, and advanced data treatments.
- Strategic partnerships with industry stakeholders and technology providers.
- A set of pilot projects, in R&I partnership with industry, to explore the subsurface faster, deeper, and more efficiently with innovative technologies and efficient geological characterisation.

Action RRM1.4 – Multidisciplinary assessment of unconventional mineral resources

Expected outcomes:

- Inventory of the resource potential of brines (e.g., lithium, bromine, alum shales) related to geothermal systems or sedimentary basins.
- Multidisciplinary approach to assess deep/under-cover deposit potential.
- Assessment of Europe's - and in some cases international - marine mineral resources and potential using a comprehensive analysis of ore-forming processes and environments. This requires research to better understand genetic processes of marine strategic raw materials deposits, map their distribution, and characterise their properties.

Priority RRM2 – Improve responsible supply of raw materials in Europe

Developing robust, scientifically based methods for assessing the economic, environmental, and social impact of supply chains will enable analysis and comparison of the environmental and societal benefits along supply chains, from exploration and mining (key areas of activity for EuroGeoSurveys member NGSOs) to the final products, supporting critical transitions in the energy, digital, and industrial sectors.

Action RRM2.1 – Create and share comprehensive models to forecast the life cycle of mineral resources

Expected outcomes:

- Forecasts of future material flows and stocks, leveraging established tools like Material Flow Analysis and Input-Output Tables.
- Supply risk and criticality analyses carried out in relation to different prospective scenarios of demand evolution, achieved through collaboration between NGOs and organisations such as national mineral raw material observatories and industry.
- Prevent sterilisation of mineral resources through responsible land-use planning.

Action RRM2.2 – Maintain up-to-date criticality assessments for raw materials (Critical Raw Materials and Strategic Raw Materials) as an interactive dashboard for decision makers/stakeholders

Expected outcome:

- Updated and integrated models and methods to assess key parameters, e.g., reserves, production, consumption, recycling, and geopolitical factors that could impact supply risk, providing public authorities and industrial sectors access to the latest information needed to make informed decisions.

Action RRM2.3 – Build collaboration between EuroGeoSurveys and other stakeholders in the raw materials sector, particularly with national raw materials observatories

Expected outcomes:

- A European-level holistic approach to EuroGeoSurveys collaboration with raw materials stakeholders, including government, academia, policy- and decision-makers, and industry.
- An organised network accessible to R&I teams and national raw materials observatories, able to provide consolidated data to inform raw materials value chain analysis.
- Improved data integrity and reliability, and efficiency of collaboration in the raw materials R&I sector, including structured connections to stakeholders in exploration, mining, and processing, to ensure uptake of R&I.

Action RRM2.4 – Develop EU cross-border and international collaborations to support European raw materials resilience

Expected outcomes:

- Support for implementation of EU cross-border strategic partnerships on raw materials, including technical actions, cooperation on R&I, capacity building, and knowledge sharing. Focus on large ore-forming geological systems (e.g., Scandinavian Shield, Variscan Belt,...).
- Strengthened organisational-level international geoscience diplomacy in raw materials, contributing to raised awareness of the relevance of geoscience for policy at international level.
- Strengthened international geoscientific expert networks in raw materials using ICE SRM EU Platform.

Action RRM2.5 – Develop data, tools, and methods to assess the environmental and societal impacts of supply chains, using a stakeholder co-designed and multidisciplinary approach

Expected outcomes:

- Contribute to the development of Life Cycle Assessment data and methods adapted to mining and quarry sector needs. This includes creating new indicators, improving database reliability, and managing uncertainties within supply chain analysis.

- This interdisciplinary approach is needed to address the challenges and drivers influencing the notion of social licence to operate in the mining and quarrying sectors, and NGOs can provide valuable input at local and EU scales in that field. Assessment of the environmental and social impacts, including the understanding of social engagement drivers, is certainly key to improve responsible supply.

Priority RRM3 – Support the development of responsible mining and a circular economy

Minimising the environmental impact of the mining sector requires developing and promoting responsible methods across the entire mining life cycle, from exploration and extraction to processing, refining, mine closure, and recycling. While the primary focus of NGOs lies in exploration and post-mining activities, their expertise plays a vital role in environmental and impact assessments of these activities. Also, unlocking the vast potential of Europe's existing mining waste – abandoned sites, current waste rock, tailings, and metallurgical residues – is crucial to sourcing 10% of the EU's annual production from within the Union, as required by the CRM Act. These secondary sources represent a valuable resource of critical and strategic raw materials. By first characterising these potential secondary resources and using optimised reprocessing and environmentally friendly techniques, Europe can significantly reduce its reliance on external resources and move closer to achieving the targets set by the EC.

Action RRM3.1 – Through co-design with industry and policymakers, develop innovative and non-invasive observation, data acquisition, and data processing tools (multiscale and multisource) to support the full mine life cycle

Expected outcome:

- Innovative exploration, mining, and processing techniques that minimise environmental impacts, as well as automated monitoring of mining activities and environmental impacts (e.g., Earth observation tools, UAVs, contributing to e.g., water treatment, tailings management, dust prevention, improved biodiversity and geoconservation, mine site remediation, etc.).
- Technical tools and expert decision-support structures to support data-informed interaction between operators and policymakers.

Action RRM3.2 – Using stakeholder engagement, assess local socio-environmental-economic ecosystems of abandoned and existing mines

Expected outcome:

- Applied tools and methods to maximise resource efficiency and economic benefits, while minimising environmental impact.

Action RRM3.3 – Update knowledge of the raw materials potential of European mining waste (left materials & processing wastes)

Expected outcomes:

- Ongoing maintenance and update of a database of European mining wastes delivering (through EGD) access to up-to-date secondary raw materials data, with common EU standards, building on the GSEU project. This includes data harmonisation using UNFC and INSPIRE standards.

- Methods and workflows for systematic physical and chemical characterisation and assessment of mining wastes (including tailings and processing wastes) to optimise recovery and minimise environmental impact. This will draw on data from all available sources, including industry, and will support application of the UNFC to characterise and map mine dumps and other potential secondary mineral resources. Methods will combine observation techniques (remote sensing to field mapping), volume calculations, and geochemical analyses to quantify resource potential, focussing also on risk assessment.

Action RRM3.4 – Promote innovation and new technologies for abandoned mining wastes recycling to allow economically viable mineral extraction

Expected outcomes:

- Innovative processing technologies for economic extraction of raw materials from mining wastes. New approaches will address challenges inherent in low grade deposits, e.g., increasing processing volumes, improving separation efficiency, and minimising environmental footprint.
- Pilot R&I projects in partnership with industry, focussing on innovative recycling concepts and technologies adapted to tailings and mining wastes.

Priority RRM4 – Improve visibility and coordination of aggregate resources across Europe

Aggregates may not be considered critical minerals in the traditional sense, but they are the largest-volume raw materials used in construction and coastal protection and both onshore and offshore resources are under pressure from e.g. land-use conflicts and environmental protection. The European Union is investing heavily in transport corridors, renewable energy infrastructure, flood protection, and housing development and long-term access to large quantities of aggregates is essential. A common European overview of resources will help to ensure sufficient construction materials while minimising transport and associated emissions and provide planners with the necessary information on available resources.

Action RRM4.1 – Establish a reliable and harmonised overview of aggregate resources

Expected outcomes:

- Reduction in aggregate supply uncertainty and bottlenecks, identify alternative supply sources, respond more effectively to regional shortages and improve economic competitiveness, strategic resilience and sustainability.
- Support of the green transition by ensuring sufficient aggregates for renewable energy installations, grid expansion, rail infrastructure and climate adaptation measures.
- Qualitative and quantitative maps of source to sink and residence time of sand in the continental shelf.
- Greater use of secondary resources by the integration of both primary aggregates and recycled construction materials, reducing pressure on virgin deposits, and contributing to EU circular economy goals.

GOAL: Sustainable Management of Groundwater in a Climate Change Context (GW)

Groundwater is essential for drinking water, economic development, and the functioning of ecosystems. Climate change is impacting this precious resource and mitigation and adaptation strategies must take account of groundwater systems, which can be part of the solution but also a vulnerable end-member. Climate change is a key issue when tackling the overarching challenges for water resources, including the restoration of a good quantitative and chemical status for all groundwater and a good ecological status of surface water bodies in Europe as stipulated by the Water Framework⁶ and Groundwater Directives⁷ and associated guidance^{36, 37}. The need for new strategies and knowledge of the climate change challenges to improve water resources resilience in general is furthermore emphasised in the new European Water Resilience Strategy⁸ and specifically for groundwater in the new EEA report on groundwater resilience³⁸.

Achieving these goals requires transdisciplinary research and sound understanding of interactions between groundwater and surface water status and uses, and between on- and offshore groundwater and groundwater-dependent terrestrial and associated aquatic ecosystems as well as ecosystems within groundwater itself. Integrated use of groundwater and surface water is imperative to ensure good quantitative and chemical status of both, sustain legitimate and sustainable uses (drinking water, agriculture, industry) and ecosystems, and bring freshwater use back within planetary boundaries³⁹. Pressures on quantity and quality of groundwater and surface water include climate- and land-use changes, contamination from industrial, agricultural and urban sources, and freshwater abstraction for competing use⁴⁰ in connection with the green transition. These pressures are exacerbated by decreasing funds for environmental protection at both national and European levels and relaxation of measures that limit use of groundwater and prevent contamination in agricultural contexts.

Water Framework and Groundwater Directives

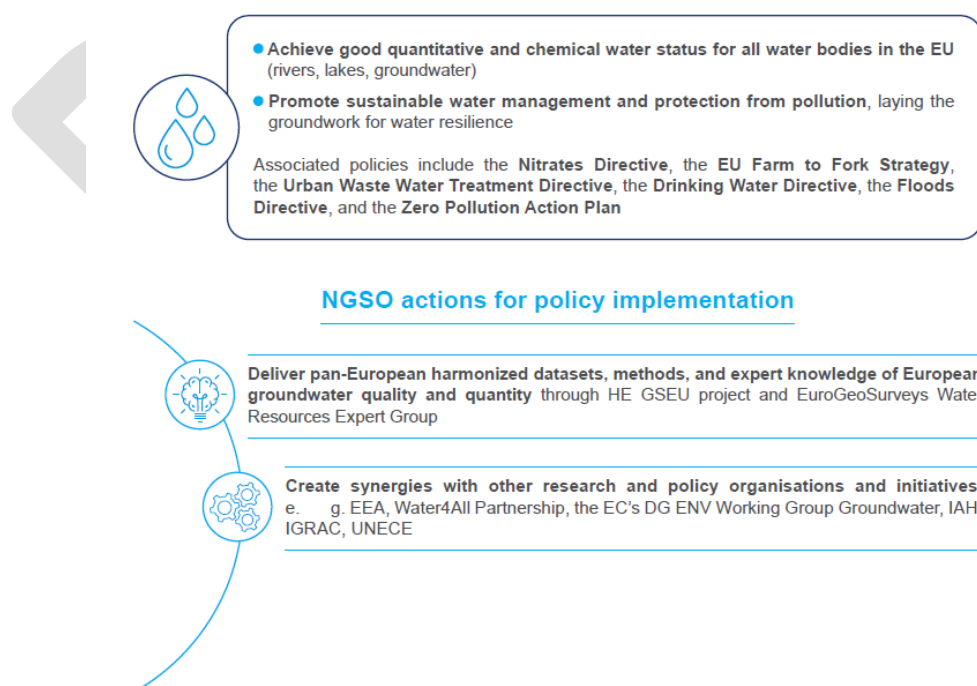


Figure 17: Key geological information services related to the Water Framework and Groundwater Directives.

The R&I actions in this goal aim to deliver a sound geoscientific background, supporting society to sustainably manage groundwater resources and providing good groundwater chemical and quantitative status and to concretely realise the following outcomes:

- Dedicated geoinformation products, such as map viewers, databases, and integrative IT platforms hosting standardised data and information about groundwater quantity and quality monitoring, such as the European Groundwater Monitoring Database (EUGM), including cutting-edge near real-time measurements and advanced interpretation techniques.
- Advanced modelling and visualisation tools to inform water authorities and the public about the projected effects of human actions, impacts of land-use changes, and climate change mitigation and adaptation measures. This includes development of integrated groundwater-surface water models to quantify effects of hydroclimatic changes, extreme events and temporal trends.
- Up-to-date methodologies to integrate groundwater flow, reactive transport, and travel time modelling of pollutants that can describe the functioning of groundwater systems related to the protection of drinking water and the restoration of groundwater-dependent terrestrial and - associated aquatic ecosystems.
- Methods to derive groundwater residence-time distributions which empower the assessment of groundwater resource vulnerabilities and inform about realistic timelines for reaching remediation targets, given the history and fate of contaminants in groundwater bodies in current and changing climate.
- Groundwater assessment and forecasting approaches as early-warning systems to quantify the evolution of water tables and the short and long-term risk of floods and droughts.
- Groundwater chemical monitoring and forecasting methods to measure the evolution of contamination in reaction to contamination pulses and source measures that aim to reduce further contamination.
- Improved understanding of the relation between elevated concentrations of geogenic elements and contaminants in groundwater and their impact on human and environmental health.
- Integrative approaches based on sound geoscientific knowledge and 4D geocharacterisation to evaluate and balance competing subsurface uses in relation to drinking water, mining of (critical) minerals, CCS, storage of heat, gases and solutes, exploration of geothermal energy including the effects on temperature, salinity, cross-contamination, groundwater ecosystems, and water use.
- Efficient use of artificial intelligence in combination with the classical hydrogeological methods.



Figure 18: EuroGeoSurveys Sustainable Management of Groundwater actions contribute to delivering on these UN SDGs.

Priority GW1 – Integrating climate and groundwater-surface water monitoring and modelling for impact assessment and projection, climate change mitigation and adaptation, and subsurface inclusive spatial planning

Effective management approaches are required to develop sustainable groundwater management strategies in response to changing hydrological conditions and climate scenarios. These management approaches rely on sound geoscientific understanding of groundwater systems and their hydrogeological and hydrogeochemical interactions with surface water and meteorological and climatic conditions. Floods and droughts will have huge economic effects on society by damaging infrastructure, the built environment in general, and ecosystems. Hence, monitoring of water tables to forecast floods and droughts is needed across Europe to protect society and nature and minimise the costs of extreme climate events. We argue that integrated (coupled or hybrid) hydroclimatic, groundwater-surface water, and coastal-marine water interaction modelling (calibrated using near real-time monitoring data) as well as integration of satellite data (e.g., GRACE, InSAR) will help identify vulnerable and resilient groundwater bodies and groundwater-dependent terrestrial and aquatic ecosystems, prioritise adaptation and mitigation measures, and develop sustainable water management strategies. There is a need to reconcile differences in spatial and temporal scales to address fragmentation and to incorporate uncertainties in climate projections and hydrological parameters, and account for complex feedback mechanisms between surface water and groundwater systems. Using large scales and transboundary settings is necessary, as is sharing scenarios, parameters, and model outputs, requiring collaboration between NGSOs and other organisations, ensuring trans and inter-disciplinarity. Groundwater models and related data, including AI tools, should support increased understanding of the complex interaction of subsurface urban infrastructure and aquifers. They should also provide data, information, and knowledge to support development of the upcoming IPCC Special Report on Climate Change and Cities⁴¹.

Action GW1.1 – Improve data availability at different spatial scales, from local to global

Expected outcomes:

- Dedicated geoinformation products, such as map viewers, databases, and integrative IT platforms hosting information about standardised groundwater quantity and quality monitoring data, such as the EUGM, including cutting-edge near real-time measurements and advanced interpretation techniques.
- Methods to integrate past and current monitoring data, focusing on groundwater level status trend detection, forecasting and optimisation of data flows, developing state-of-art databases and information, and communication technology tools as potential early-warning systems.
- Advanced monitoring, modelling and visualisation tools to inform the public of projected effects of human actions and impacts of land-use changes and climate change mitigation and adaptation measures, including the further development and enhancement of integrated groundwater-surface water models (GW1.2), to quantify the effects of hydroclimatic changes and temporal trends.
- Further implementation and application of field sensors, and information and communication technology tools (e.g., real-time sensors, smart meters, smartphone applications).
- Increased information density and transparency over water use and availability to raise societal awareness (e.g., using citizen science supported techniques).

- ML-aided techniques applied to extend the available information to data-scarce areas (e.g., in combination with hydrological modelling and satellite data).
- City-scale groundwater monitoring networks implemented to support urban climate change mitigation and adaptation and water resilience, security and safety in urban areas.

Action GW1.2 – Develop scientifically sound hydrogeological models integrating climate, surface, and marine water interactions

Expected outcomes:

- Improved, integrated modelling frameworks, accounting for uncertainty and variability.
- Multi-scale modelling frameworks that capture interactions between local-scale hydrological processes and regional-scale climate patterns, and account for surface and subsurface spatial heterogeneity in hydrogeological properties, land-use, and topography that affect risk of floods and drought.
- Up-to-date methodologies to integrate groundwater flow, reactive transport, and travel time modelling of pollutants that can describe the functioning of groundwater systems related to the protection and restoration of associated ecosystems (e.g., tools to quantify groundwater microbial activity, which is beneficial for groundwater quality).
- Improved hydrogeological modelling tools, with better geological delineation, enabling simulations of continuity of the water cycle, from precipitation, surface flow, unsaturated flow to the groundwater table, groundwater flow in aquifers and the outflow to a large variation of spring types (e.g. limnocrene and rheocrene), to receiving surface waters and submarine ground water discharges.
- Integrated AI tools to support the development of hydrogeological models, including testing and development of xLSTM for water level prediction and more AI models in coastal areas.

Action GW1.3 – Understand groundwater residence/travel time distributions as key factors for vulnerability assessment to global change impacts on groundwater systems

Expected outcomes:

- An environmental tracer database for assessing groundwater vulnerability across Europe, based on tritium/³He and other age tracers, and extending information from tracers using ML methods.
- Combined environmental tracer and modelling derived groundwater residence-time distributions which empower assessment of groundwater resource vulnerabilities and inform on timelines for reaching remediation targets, given the history and fate of contaminants in groundwater bodies in a changing climate.
- Innovative tracer-assisted and -calibrated groundwater modelling approaches.

Priority GW2 – A portfolio of groundwater-related solutions including adapting to climate change, groundwater, and surface water resilience, security, and safety in rural and urban areas

In recent years, nature-based solutions (sometimes in combination with engineered solutions, i.e. hybrid), have become important in climate change adaptation and water conservation strategies supporting sustainable water management. In urban contexts, nature-based solutions (often implemented as, e.g., green spaces, bioswales to retain excess subsurface water) have contributed to

mitigating risks for urban flooding and damage to housing and infrastructure while harvesting co-benefits including more attractive urban environments and benefits to public health. In rural contexts, nature-based solutions are implemented to retain and store surface water by primarily river, lake, and floodplain restoration and from runoff events. Nature-based solutions can utilise the buffer capacity of subsurface shallow groundwater to store retained water, notably by means of Managed Aquifer Recharge (MAR) to deal with both increased flood and drought risk. Nature-based solutions provide multiple benefits besides flood and drought mitigation, including enhancement of biodiversity and carbon sequestration (particularly in the case of peatlands and wet forests), and facilitating underground storage facilities.

Action GW 2.1 – Assess and deliver nature-based solutions for integrated quality and quantity groundwater management

Expected outcomes:

- Tools and models to identify vulnerable areas and improve groundwater monitoring to support targeted water conservation strategies, including using nature-based solutions. This will ensure more resilient and sustainable water supply. Sustainable water management is essential to mitigate flood and drought risk, ensure safety of citizens, and urban and rural water security.
- Assessment of the impact and efficiency of mitigation solutions on groundwater, including nature-based⁴² (or hybrid) strategies, urban and industrial wastewater reuse, nature-based water treatment systems (e.g., soil-aquifer treatment), and MAR to promote the increase of mitigation options in Europe.
- New, improved, and integrated surface and subsurface monitoring tools for management and protection of water resources and impact assessment and design of climate change mitigation and adaptation solutions. Advanced monitoring systems for emerging pollutants are proposed and tested in pilot areas and on operational scale for MAR, and soil-aquifer treatment systems. For MAR, special focus is placed on efficient screening tools for emerging pollutants such as human and veterinary pharmaceuticals, personal care products and their metabolites, and persistent compounds such as Per- and polyfluoroalkyl substances (PFAS) and microplastics and antimicrobial resistance. Improved tools and methodologies to characterize aquitards, which function as important barriers to groundwater contamination of deep (paleo)water, and which determine the interactions between renewable groundwater and paleo groundwater resources.

Priority GW3 – Protecting Groundwater in relation to drinking water, ecosystems, and public health

The need to revise the Water Framework^{Error! Bookmark not defined.}, Groundwater Directive^{Error! Bookmark not defined.}, Environmental Quality Standards Directive⁴³, and Drinking Water Directive⁴⁴ has led to numerous discussions on the need for, and means of, monitoring chemical substances and microplastics in groundwater across all member states. The sheer number of chemical compounds (listed under the REACH regulation⁴⁵) and their metabolites and complex interactions is a major challenge for water quality assessment and mitigation. Basic questions, e.g., how to efficiently monitor all parameters

affecting the chemical and ecological status of groundwater and associated ecosystems, require further development and standardisation of new monitoring techniques. The ecological status of dependent ecosystems is strongly related to groundwater quantity and quality. Water quality monitoring needs further development of non-target analyses towards standardisation and combination with quantitative assessment. There is a need for time-integrated measurements of pollutants in groundwater (e.g., passive sampling) and other ‘omics’ technologies (e.g., environmental DNA indicators), for a first step toward the assessment of the ecological status of groundwater itself (microbial and stygobiotic communities).

Action GW 3.1 – Tools to address groundwater contamination in relation to public health

Expected outcomes:

- Up-to-date methodologies to relate groundwater contamination patterns and trends reflecting historic and current emissions, considering the reactivity of the subsurface and travel times through unsaturated and saturated zones.
- Monitoring techniques and knowledge transfer on microplastics, antimicrobial resistance, pharmaceuticals, cosmetics, and PFAS. Advancement of groundwater monitoring through the analysis of the full geochemistry package and the definition of new inorganic pollutants arising from anthropogenic activities including potential pollutant degradation by oxic and anoxic microbial communities.
- Forecasting approaches to quantify evolution of groundwater contamination in abstraction wells, natural springs, and receiving surface waters in reaction to contamination pulses and source measures that aim to reduce further contamination, with special attention to time lags between measures and resulting breakthrough of solutes in relation to contamination legacies.
- Methodologies to quantify the buffer capacity of the subsurface including active microbial communities in relation to prolonged diffuse contamination of shallow groundwater, and reactivity of subsurface sediments and turnover times and renewal times of groundwater within aquifers and aquitards.
- Expanded and curated non-target analyses reference databases for European main groundwater bodies to facilitate compound identification and classification, and standardised protocols and quality assurance procedures to improve reliability of non-target analysis results.

Action GW 3.2 – Improve monitoring tools for assessing groundwater chemical and quantitative impacts on ecosystems

Expected outcomes:

- Increased number and quality of monitoring data on surface-water/groundwater interaction using (near) real-time monitoring sensors for both quantity and quality and ecology (e.g., eDNA, physical and chemical parameters), combined with remote-sensing technologies to improve the understanding of climate change impacts on groundwater quantity and quality as well as groundwater ecosystems and groundwater-dependant ecosystems.
- First steps towards impact-based monitoring, e.g., integration of non-target analysis with other omics approaches to elucidate complex interactions between pollutants, organisms, and ecosystems and understand effects of chemical exposure on environmental and human health.

- Improved water table measurements at important and sensitive groundwater-dependent terrestrial and dependent or associated aquatic ecosystems (rivers, lakes).

Priority GW4 – Groundwater and the green transition

The green transition requires protection of groundwater quality and sufficient quantity in the process of extracting and managing natural resources, including (critical) mineral resources, CCS, and geothermal energy. Geosciences, and in particular water resources, research must further contribute to understanding interconnectedness, interdependencies, and trade-offs between management of groundwater and the green transition. Addressing this requires innovative modelling approaches. As climate change and other global change drivers (e.g., population growth, urbanisation, and land-use change) intensify pressures on water resources and affect the green transition, integrated climate-surface water-groundwater models are needed to understand the role of these drivers and develop adaptive water management strategies and resilience measures. For an effective green transition, “strategies are also needed to mitigate potential water risks for energy storage solutions, including pumped hydropower, as well as mining...”⁴⁶. Although most solutions towards a net-zero society involve freshwater, “low emission energy scenarios often lack quantification of impacts on water quality and ecosystems, which must be incorporated into national and regional planning.” The cross-disciplinary nature of the NGSOs, particularly in relation to urban geology (priority URB1), geothermal energy (priority ETD1), and environmental risk including groundwater ecosystems or the resources-society-nature system in general (priorities MGER2, MGER3), provides a strategic position from which to approach adaptation solutions, accounting for multiple aspects of the subsurface and enabling subsurface spatial planning⁴⁷.

Action GW 4.1 – Dealing with competing uses in a busy subsurface environment

Expected outcomes:

- Integrative approaches based on sound geoscientific knowledge and 4D geocharacterisation to evaluate and balance competing subsurface uses in relation to drinking water, mining of (critical) minerals, CCS, storage of heat, gases and solutes, exploration of geothermal energy including the effects on temperature, salinity, cross-contamination, groundwater ecosystems, and water use.
- Advanced modelling tools to study interactions between drinking water storage and abstractions, heat production and storage, and cross-contamination between subsurface compartments.
- Revision of directives tackling groundwater (WFD, GWD, Soil Monitoring Law) as well as adapting of legislation surrounding CRM exploration to ensure compatibility and address competing interests.

GOAL: Managing Geohazards and Environmental Risks (MGER)

Geohazards (e.g., earthquakes, volcanic eruptions, tsunamis, sinkholes, landslides, soil erosion, radon emissions, among others) pose growing challenges as populations increase and become more urbanised, while suffering increasing climate-related pressures. **Europe's nature is in alarming decline, with more than 80% of habitats in poor condition, and the EU Biodiversity Strategy sets binding targets to restore onshore and offshore ecosystems.** Weather- and climate-related extremes caused economic losses estimated at EUR 738 billion from 1980–2023 in the EU⁴⁸. Critical infrastructure (nuclear facilities, dams, etc.), urban and coastal environments, and cultural heritage are especially vulnerable, potentially leading to cascading disasters (e.g., flooding in Slovenia and Greece causing landslides, 2023; La Palma eruption, 2021). Concentration of population in coastal regions is increasing and so is their exposure to coastal hazards (erosion, coastal retreat, subsidence and flooding). Although some natural geohazards are beyond human control (e.g., earthquakes, volcanoes), governments, communities, and individuals can implement measures to mitigate risks and enhance resilience. Human-induced hazards (triggered or exacerbated by human activities, e.g., land-use changes, industrial activities, mining, excessive groundwater pumping, intensive agriculture, and resource extraction) are often more predictable and preventable through careful management, spatial planning, regulations, and mitigation strategies.

The EU has several regulations and initiatives related to geological hazards, primarily under the broader framework of disaster risk management and environmental protection, which are at the heart of international agreements, including the Treaty of Lisbon⁴⁹ and the Sendai Framework⁵⁰:

- **EU Civil Protection Mechanism:** This mechanism facilitates cooperation among EU Member States in disaster prevention, preparedness, and response. It includes measures for dealing with natural and human-induced hazards, including geological hazards.
- **European Disaster Risk Management:** The EU has policies aimed at reducing disaster risks through preventive, preparedness, response, and recovery actions. These policies address various natural hazards, including earthquakes, landslides, and volcanic eruptions.
- **EU Thematic Strategy for Soil Protection**⁵¹: This strategy includes measures to address soil threats (e.g., landslides and erosion), emphasising national mitigation and remediation.
- **EU Nature Restoration Regulation:** First continent-wide, comprehensive law of its kind setting targets to restore degraded ecosystems, including those with the most potential to capture and store carbon and to prevent and reduce the impact of natural disasters.
- **EN Eurocodes**⁵²: These are a series of 10 European Standards, EN 1990–EN 1999, providing a common approach for the design of buildings and other civil engineering works and construction products. They are the recommended reference for technical specifications in public contracts, integrating seismic hazard. In 2026, the Second Generation EN Eurocode parts were distributed by CEN to the National Standards Bodies no later than 30 March 2026.

Furthermore, resilience has become a topic of priority at EU level, including resilience from natural disasters, therefore geohazards and environmental risks are directly relevant to some of these initiatives e.g., European Preparedness Union Strategy and the ongoing transposition of the Critical Entities Resilience Directive (CER)^{53,54}.

The main expected outcomes for the R&I actions in this goal are directed at:

- **Improving understanding of geohazard events and environmental risks**, onshore and offshore, including human-induced and multi-hazard approaches and their integration into early-warning and predictive systems.
- **Delivering better quantification of geohazard processes and related impacts** by integrating subsurface data, cutting-edge earth observation monitoring, and high-performance models.
- **Establishing coherent European common data management and risk mapping approaches.**
- **Improving risk assessment and mitigation** using more detailed mapping of susceptibility, hazards, vulnerabilities, and risks adapted to decision-making and utilisation in both early-warning or predictive systems. Advising for European legislation. Improving early-warning systems.
- **Improving soil health** by delivering methods for monitoring and assessing soil quality^{55,56,57}.
- Supporting maritime, land and urban spatial planning by integrating geohazards knowledge.
- Supporting marine and land nature restoration projects and plans by providing the necessary geological background knowledge.

Treaty of Lisbon & Sendai Framework



NGSO actions for policy implementation

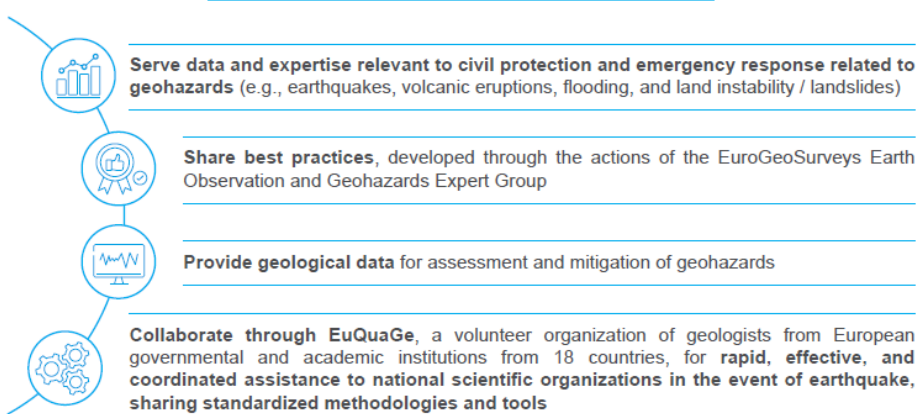


Figure 19: Key geological information services related to the Treaty of Lisbon and Sendai Framework.



Figure 20: EuroGeoSurveys Managing Geohazards and Environmental Risks actions contribute to delivering on these UN SDGs.

Priority MGER1 – Improve understanding of natural and human-induced geohazard events: towards forecasting

Understanding geohazard events is essential for assessing and mitigating associated risks in the continental, coastal and marine environment. Research should address the most common hazard-related questions: what? why? how? where? when? employing a wide range of methods and techniques (e.g., geological and geophysical surveys, remote sensing, in-situ testing, big data analytics, AI including ML, stochastic and multiphysics modelling, automated AI-based monitoring tools). These approaches enable more accurate mapping, monitoring, analysis, and forecasting of geohazard events, informing effective risk reduction strategies and enhancing community resilience.

Field observations and advanced technologies such as satellite imagery, InSAR, aerial surveys, and ground sensors (e.g., optical fibre) are revolutionising understanding of geohazards. This surge in data enables extensive area mapping, real-time information collection, and deeper insights. The recent European Ground Motion Service from Copernicus provides consistent and reliable information regarding natural and anthropogenic ground motion across Europe by analysing long time-series of radar data. Additionally, the recent improvement in InSAR (Interferometric Synthetic Aperture Radar) technology and the planned future satellite missions by the European Space Agency, with the deployment of L-band sensors, is increasing the capacity to observe ground deformation, one of the many technological advancements influencing how we understand and forecast geohazards. In this context, the rise of AI approaches is also enabling a more efficient combination and analysis of large datasets of different time series, allowing for the identification of relationships between ground motion and environmental drivers (soil moisture, rainfall, etc.) and of precursor signals for events like landslides. This information is key to understanding future response of slope conditions with climate change.

Although Earth observation data makes major contributions to addressing relevant issues, knowledge of the geological structure and the hydrogeological conditions of the subsurface are essential both for understanding the phenomena detected and for developing targeted solutions. For example, geochemical baseline studies allow for hazard-related pollution/contamination to be detected and addressed.

The development of new stochastic and multiphysics models able to numerically simulate reality is a multifaceted process that involves a variety of activities tailored to the type of model. Models provide tools to understand, define, quantify, visualise, or simulate how a phenomenon or geo-system behaves. If the proposed model can reproduce past and present behaviour, it could be used for forecasting the future (4D modelling). A challenge lies in developing realistic models able to consider the complexity of processes involved, working on multiple scales and timeframes, and managing uncertainties.

Action MGER1.1 – Innovate mapping and monitoring of geohazards by increasing the use of Earth observation through new technologies and advanced sensors

Expected outcomes:

- Integration of diverse data sources to create methods for combining data from spaceborne, aerial, ground-based sources, and submarine smart cables to gain a comprehensive view of geohazards.
- Implementation of advanced data analysis techniques using AI, to identify patterns and insights from Earth observation data, leading to a more comprehensive understanding of geohazards.

Action MGER1.2 – Develop new stochastic, multiphysics, or mixed models: towards Digital Twins and forecasting

Expected outcomes:

- Stochastic models, using Earth observation data and AI, to identify dependencies, cause-effect relationships, and empirical geohazard forecasting.
- Multiphysics models calibrated using Earth observation data, to identify realistic numerical simulations, and quantitative geohazard forecasting.
- Mixed models, combining stochastic and multiphysics approaches, to smooth uncertainties.
- Improved interoperability and integration of different types of models and digital twins across spatial and temporal scales which would also allow analysis of spatial and temporal relationships among different hazards (e.g., floods and landslides).

Action MGER1.3 – Analyse EU land subsidence and uplift regarding natural and anthropogenic activities

Expected outcomes:

- Comprehensive harmonised analysis of the EU InSAR data (EGMS) to map the areas of land subsidence and obtain characteristic trends.
- Delineation of unstable areas using the characteristic patterns in InSAR data (seasonality, presence of acceleration/deceleration), and their link with topography, geomorphology, and geology in order to provide an interpretation on the source of the observed motion (landslide, subsidence, mining, etc.). Correlation of the trends and areas of subsidence and uplift with site geology water table levels, human activities (e.g., mining, water extraction) and climate change effect (e.g., permafrost melt).
- Risk analysis for individual areas, including elements at risk such as the estimation of the exposed population.
- A basic insight and forecasting tool utilising AI, providing advanced insights into the causal effects of subsidence and basic future scenarios to the public, policymakers and industry.

Priority MGER2 – Risk assessment and mitigation

Risk is a function of how a hazard combines with vulnerability and exposure. Understanding these relationships makes it possible to identify ways to reduce risks, either by reducing hazard intensities or frequencies, or by decreasing exposure and/or vulnerability. From an operational viewpoint, identifying areas prone to hazards enables authorities to implement spatial planning measures to reduce their

impact on communities and infrastructure. Conversely, infrastructure development and construction standards must account for likely geological hazard event magnitudes to ensure longevity and resilience.

To effectively manage risks and disasters, national and civil protection authorities require spatial data depicting the potential impacts of geohazards in their continental and marine territories. When disasters transcend borders, inconsistencies in decision-making processes (e.g., scale, hazard zoning, impact representation) can create challenges in transboundary collaboration. A homogeneous understanding of geohazards at the European scale fosters more effective risk reduction strategies and preparedness efforts for assets that can span different countries (transport corridors, energy network and telecommunication cables). At the same time, close co-operation with local authorities and institutions is required as geologically induced risk is heavily dependent on the area under consideration (e.g., higher resolution is required for urban areas). Approaches such as the Urban Geo-climate Footprint (UGF) methodology support the characterisation of human settlements according to their geological and geographical settings, enabling a better understanding of local pressures and vulnerabilities, supporting geohazard risk assessment and resilience.

Knowledge of past events is crucial for understanding the spatial distribution, frequency, and severity of geohazards. Standardising data collection ensures consistent information quality, which facilitates transparent data sharing and collaborative analysis.

Action MGER2.1 – Continuous updating of inventory and geohazards database

Expected outcomes:

- Refined standardisation of geohazard event data collection and management practices at continental scale.
- Robust system for maintaining a continuous inventory and updating a geohazards database.
- Improved systems allowing the quantification and recording of the impact (loss of life, financial cost, recovery time) of natural hazards, to support more effective risk assessment and decision-making.
- Analysis of non-traditional information sources (e.g., newspapers and social media) to provide additional information on geohazard occurrence and impact.

Action MGER2.2 – Establish coherent and common risk mapping approaches across Europe

Expected outcomes:

- Unified system for risk representation. This standardisation should encompass Mapping Levels, ensuring consistent maps across regions, and Numerical Web Services, enabling seamless data exchange and collaboration through standardised web services.

Action MGER2.3 – Improvement of susceptibility, hazard, and risk maps

Expected outcomes:

- New susceptibility and hazard models and maps across different spatial scales and timeframes.
- New quantitative vulnerability models and maps across various scales, from individual buildings to entire regions. These tools should consider both physical infrastructure (structural vulnerabilities) and social, economic, and environmental factors (systemic vulnerabilities).
- New quantitative risk models and maps across different spatial scales and timeframes, particularly integrating models with longer-scale forecasting models. Considering factors such

as structural integrity (building level) and systemic weaknesses (territory level) will allow more precise risk maps, risk assessments, and prioritisation.

Action MGER2.4 – Integration of geohazard information for mitigation and societal resilience

Expected Outcomes:

- Systematic integration of geohazard knowledge and forecasting into urban planning
- Interoperability of data on geological hazards and risks with other types of risk data or emergency response systems, created for instance as part of the CER.
- Deployment of AI chatbots to assist with providing insights into critical databases and user-friendly ways to interpret the data.

Action MGER2.5 – Improvement of early-warning systems

Expected outcomes:

- New early-warning systems for geohazards, including multihazard approaches, integrating subsurface data, real-time cutting-edge Earth observation monitoring, and high-performance models.
- Development of alarming systems and sensors that enable detection of early signs of land movement.

Priority MGER3 – Reduce pollution and improve soil health

Healthy soil is a fundamental prerequisite for human existence. Many NGSOs in Europe contribute to the monitoring of soil quality and properties, mostly for urban and industrial soils, but also for land management purposes. That mission is complementary to soil quality for agricultural uses, which is usually handled by other organisations. Soils have been overexploited globally partly due to lack of soil protection policies, and the soils are now under threat from degradation (e.g., erosion, contamination, sealing). Soils play a vital role not only for food production but also indirectly for water storage and groundwater recharge and purification. Regarding climate change adaptation, soil management will play a major role in mitigating drought, floods, forest fires and other extreme weather events. Anthropogenic pressure on soil is steadily growing; in the EU alone, approximately two-thirds of soils face degradation risk because of inadequate management practices. The EU's 2050 Zero Pollution Ambition⁵⁸, encompassing clean air, water, and soil, entails reducing pollution to levels that no longer pose a threat to human health and natural ecosystems, creating a near-pollution-free environment. Achieving this ambitious objective necessitates swift and coordinated action throughout Europe.

This priority focusses on delivering data, geological expertise, and methodologies for monitoring and assessing soil quality to make informed decisions related to land-use dependent developments.

EU Soil Monitoring Law



- Establish a comprehensive and consistent monitoring framework allowing regular and accurate assessment of soil health
- Long-term objective of all EU soils in a healthy condition by 2050.

NGSO actions for policy implementation

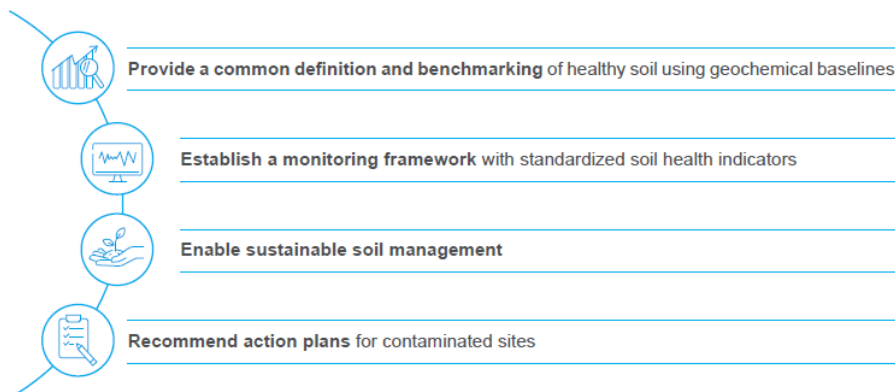


Figure 21: Key geological information services related to the EU Soil Monitoring Law.

Action MGER3.1 – Establish Natural Background Levels for soil chemical and physical properties

Expected outcomes:

- Definition of natural chemical baselines for European soil at various scales, to identify areas suffering from pollution or nutrient deficiency. Both can be remediated by successful soil management practices, once recognised.
- Geochemical background and threshold values are established for potentially toxic elements (PTEs) in soil. Their sources are identified and described, considering soil type, climate, and land-use, and adapted to the regional and local scale.
- Development of new pollution markers and calculation models for threshold or warning values of pollutants.

Action MGER3.2 – Develop standard methodologies for soil mapping and monitoring

Expected outcome:

- Definition and validation of standardised, common methods of sampling, analytical protocols, data management, and visualisation, for mapping all parameters that define soil health status.
- Improved standardisation of soil quality assessment protocols, which guarantee the broad use of soil data in the transnational environment.
- Definition of parameters best characterising the chemical status of soil in relation to geographic location, climate, precipitation conditions, and land-use specifications. This will enable efficient planning of soil monitoring campaigns, considering region-specific features.

Expected outcomes:

- Ongoing monitoring of soil erosion processes, including natural and anthropogenic erosion and related to geological parent materials. Notwithstanding, soil erosion is a long-term, large-scale process that requires systems-level management.
- Integrated understanding of soil erosion and contamination (e.g., potentially toxic metals, micro-plastics, pesticides), carbon losses, nutrient excess or loss, land degradation in the frame of climate change, and food security.

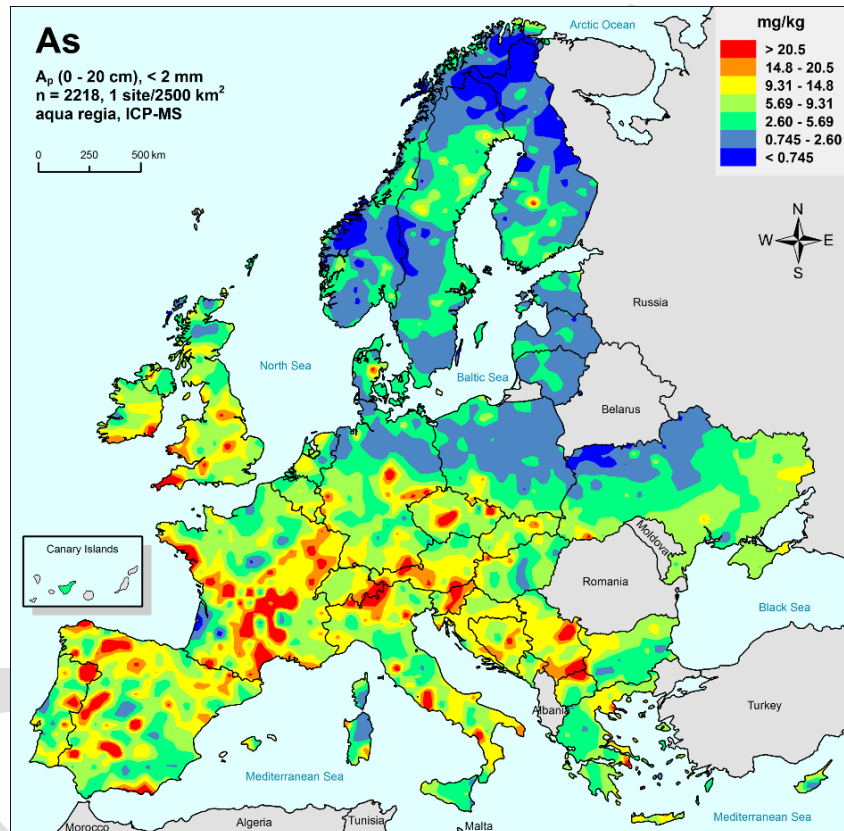


Figure 22: Pan-European distribution of arsenic concentration in agricultural soil: An example of data produced by the EuroGeoSurveys Geochemistry Expert Group.

Integrating Subsurface Management and Stakeholder Engagement

GOAL: Urban Geology (URB), Land Planning (LUP), and Geoheritage (HER)

Land management and urban planning strongly depend on subsurface conditions, properties, and resources. Europe faces growing competition for subsurface resources uses, land spatial planning and urbanisation. Managing integrated surface and subsurface management combining land and subsurface-use planning. It is urgent in urbanised areas where multiple human activities are competing for space within much smaller areas. This involves, e.g., underground secondary infrastructures such as tunnels, parking, stormwater tanks, and district heating (and cooling) networks and facilities. At larger scale the combined surface and subsurface space must also support measures mitigating climate impacts (floods, droughts, heat) and geohazards. Sustainable use of soil and natural aggregates in urban environment must be safe and not contribute to additional risks related to their chemical and physical properties. Beyond traditional uses, the subsurface is key for decarbonisation through CO₂ storage, hydrogen and energy storage, geothermal systems, groundwater management, and raw materials exploitation. Integrated spatial planning therefore requires robust knowledge of geological and hydrogeological conditions.

However, most European countries lack consistent, integrated regulations for subsurface use. Many subsurface-related policies and legislation have a siloed approach, targeting improvements within policy domains or sectors⁵⁹. To accelerate sustainable transitions, Europe must shift from fragmented, “first-come-first-served” approaches to holistic, cross-sector spatial planning that integrates subsurface and surface functions, embedding subsurface considerations into planning processes.

Urban geology has emerged as a distinct discipline with numerous interfaces with spatial planning and urban development. Significant progress is still needed to better integrate subsurface sciences with urban planning methods, tools, and information systems. At the regional scale, similar challenges can be observed, although they relate to different types of land and subsurface use, including linear infrastructure development, mineral resource exploitation, groundwater protection areas, and other subsurface activities.

New practices of ‘subsurface integrated spatial planning’ at different governance and scale levels will enable 'preparedness by design', supporting improved and more comprehensive implementation of subsurface-related European policies. A better understanding of the often complex interferences and impacts of subsurface and surface land use require continuous interdisciplinary and applied geoscientific research.

AI-driven solutions are currently emerging and will deeply change the way to integrate models and the interoperability of platforms from various environments (environment, urban networks, transports, energy, etc.), to establish urban digital twins including subsurface information. AI should be considered as a key R&I investment with a focus on interoperability.

This requires a sustainable data infrastructure at European level, connected to dataspace, but also connecting to national, regional, and local datasets. NGSOs have significant roles to play in identifying solutions for safe and sustainable use of the urban subsurface in relation to responsible, long-term spatial planning. Another important topic is dealing with the trend of data becoming less accessible, connected to, for example, critical infrastructure.

Additionally, preserving geoheritage and geodiversity as part of natural heritage is essential for ensuring that urban growth respects both natural resources and environmental sustainability.

Urban Agenda for the EU

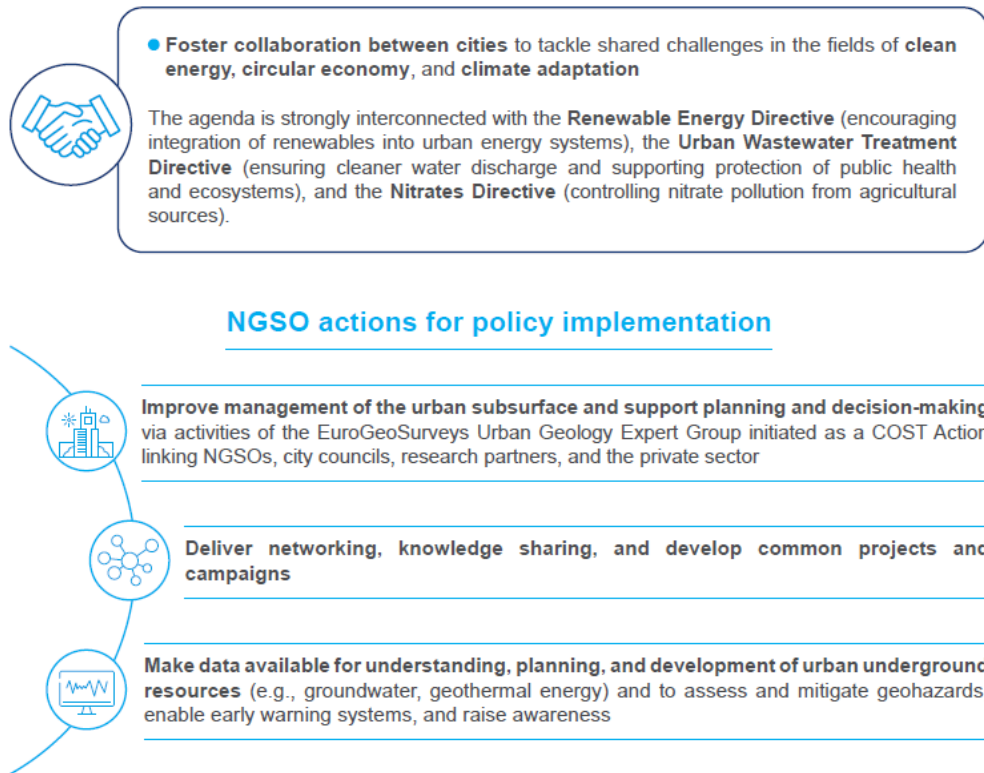


Figure 23: Key geological information services related to the EU Urban Agenda^{60,61}.

This goal relies on four components:

- **Modelling:** to understand, visualise, and resolve competing user needs of the subsurface, addressing both resources and threats with a knowledge-based approach.
- **Integration:** to foster better use of knowledge and models to produce sound spatial planning.
- **Regulation:** a framework to inform decisions and sustainable development of urban areas.
- **Social engagement:** public awareness is crucial to develop good practices for appropriate, safe, and well-balanced land-use.



Figure 24: EuroGeoSurveys actions on integrated subsurface management and stakeholder engagement contribute to the UN sustainable development goals

Priority URB1 – Urban Geology Knowledge and Modelling: A Crucial Asset for Sustainable Planning

As cities expand and become more complex and populated, integrating the subsurface into above-ground agendas is vital to ensure the stability and sustainability of key systems. The urban subsurface is recognised as a multi-use 3D space where public transport, water, electricity, gas, heat, and telecom networks coexist. This space provides critical resources such as water, space for storage or geothermal energy. It also delivers vital geological services such as water infiltration and protection or heat regulation. Subsurface characterisation is crucial for identifying and mitigating ground risks in land-use planning and construction and nature-based solutions.

As cities face risks of natural and climate-related hazards (e.g., flood, landslide, subsidence, seismic activity, volcanic activity, sinkholes, drought) and urbanisation grows, the urban subsurface must be considered in tandem with urban expansion, whether for industrial or tertiary development, using responsible, balanced land-use planning. Subsurface space can play an increasing role in decarbonising cities through technological solutions such as geothermal energy, seasonal heat and cold storage, stormwater banking, and local shallow groundwater use for irrigation, while also mitigating urban heat island effects. Also, against the frequent heat waves impacting on European countries, the subsurface insulating effects should be considered and the urban underground spaces used as climate shelters.

Integrating geological, hydrogeological, resource, and environmental data with built environment models is essential to prevent conflicts of use, manage risks, and develop innovative solutions to harness the properties of the urban subsurface. Key stakeholders—city managers, urban planners, the construction sector, and infrastructure owners—rely on this information for robust spatial planning, design of new infrastructure, and risk management and reduction. R&I is crucial for shaping future

sustainable cities. The complex and diverse tasks in urban areas require close cooperation with the relevant specialist disciplines (e.g. hydrogeology, geochemistry, geophysics, geohazards, etc.).

Action URB1.1 – Develop urban subsurface ontologies and standards compatible with Building Information Modelling standards

An effort from European and National levels should be made to assure that these urban subsurface datasets are managed, organised to be consistent and including different type of information: geology, hydrogeology, geotechnics, geophysics, geochemistry, geohazard, geoheritage. As well as climate, hydrological datasets need to be included.

Expected outcomes:

- A change through EU initiatives, to change national regulations and make data open from the surface, (i.e. the Netherlands' recent regulation framework on subsurface data)
- Common ontologies for urban subsurface mapping and 3D modelling, including terminology for anthropogenic deposits (connected to USG 1.2).
- Seamless integration with above-ground infrastructure. By aligning subsurface data with Building Information Modelling standards, professionals (e.g., engineers, architects, geologists) can integrate, view, and analyse above- and below-ground data in a standardised digital environment. Aligning subsurface data (geology, hydrogeology, geomechanics, geophysics) with Building Information Modelling (BIM) EU standards to integrate, view, and analyse above-ground and below-ground data in a single, standardised digital environment.
- A platform for use cases and best practice methods for geological mapping adapted to urban environments, with a focus on anthropogenic deposits.
- Cross-disciplinary initiative with a strengthened collaboration and networking between civil engineers, urban planners, geoscientists, and utility company personnel improves project coordination and reduces conflicts during construction and maintenance.

Action URB1.2 – 3D models to manage competing use and support urban subsurface spatial planning and decision-making

Expected outcomes:

- High-resolution, evidence-based, and digitally driven geological 3D models for urban experts to inform decision-making, incorporating key disciplines (e.g., geohazards, geotechnics, hydrogeology, geology, geophysics). Expanded urban 3D geology models (beyond environmental quality and geohazards) to include climate adaptation scenarios and sustainable energy use (connected to, e.g., GW 1.2).
- 3D models as tools for subsurface visualisation and knowledge transfer across disciplines, improving communication with urban communities and stakeholders.
- Selected cities implement 3D models as Digital Twins, serving as case studies to explore the full potential of urban geology models for planning and climate resilience. A co-design approach ensures Digital Twin models meet stakeholder needs and are accessible and understandable to non-experts, fostering community engagement.

Action URB1.3 – Analyse the geological and climate footprint of cities

Classifying cities based on their geological and climatic makeup is crucial for understanding their vulnerabilities and developing risk mitigation strategies. This approach, exemplified by the Urban Geo-climate Footprint tool⁶²⁶³, helps assess urban challenges through the lens of both geology and climate. The underlying principle is that cities with similar geological and geographical settings will likely face comparable challenges due to shared geological hazards and climate change impacts. This classification fosters awareness among non-experts and decision-makers of the complex interplay between geological conditions, climate change pressures, and human activities in cities. The Urban Geo-climate Footprint tool also provides basic information on existing resources in the cities' subsurface. The aim of this action is to classify European cities using the Urban Geo-climate Footprint method.

Expected outcomes:

- Knowledge exchange, empowering city planners to share best practices for building urban resilience.
- Increased awareness of non-experts on the urban subsurface and relative preparedness about issues and hazards but also on existing geological resources.
- Knowledge-based decision-making for actions and policies that enhance geoscience-informed climate justice.

The Urban Geo-climate Footprint Approach

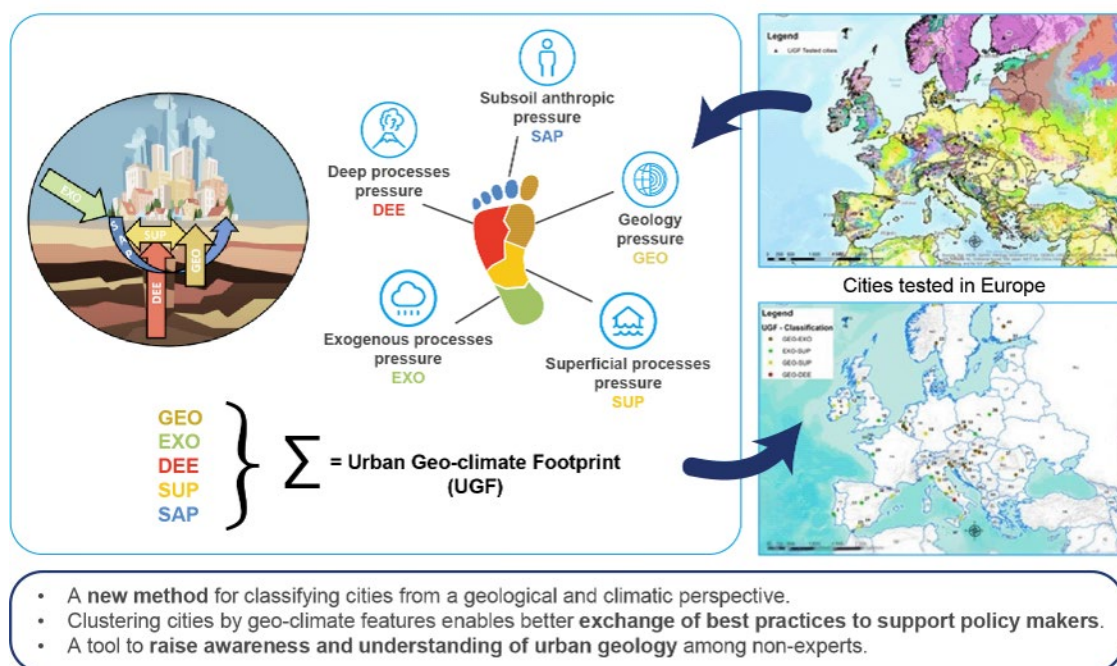


Figure 25: The Urban Geo-climate Footprint: A Framework for Assessing Urban Geological and Climate Vulnerabilities

Priority LUP1 – Land-use Planning

Land-use planning is essential for responsible and sustainable exploitation of resources. As natural resource potential often lies in the subsurface, strategic planning is needed to ensure that these resources can be accessed to avoid conflict between uses and without compromising environmental integrity and community development. Effective land-use planning involves balancing economic growth opportunities with long-term environmental stewardship, integrating geological data, and working in coordination with local communities, local authorities, industrial or agricultural users, and national policymakers. This requires a comprehensive approach to integrate subsurface-related European policies and regulations in spatial planning. Sustainable, integrated management of the geological subsurface will contribute to Europe's strategic autonomy and resilience.

By identifying areas with subsurface strategic uses (e.g., buried utility networks, underground structures, groundwater, geothermal energy, underground storage, quarries, mining,...) and aligning with land access and usage regulations, governments and industries can optimise a responsible use of the subsurface and its resources while minimising disruption to ecosystems, urban development, and other uses. This requires handling various interests both at national (potentially also transnational) and local levels and involving stakeholders of these two categories. Careful planning can also mitigate land use conflicts, ensuring that subsurface use is compatible with activities such as agriculture, conservation, cultural and social habits, and urban expansion.

Improved management and use of the subsurface at different planning levels across Europe have to be supported by FAIR data and information, applied geoscience research, and expert advice provided by a continental-scale Geological Service for Europe.

Action LUP1.1 – Strategic Land-use Planning for Sustainable Resource Exploitation

Expected outcomes:

- Identification of areas with high subsurface potential, integrated with land access and usage regulations, optimising resource extraction while preserving environmental integrity and promoting sustainable economic growth.
- Development of strategic land-use tools that balance subsurface use with competing land uses adapted to decision-making processes and communication with stakeholders, ensuring minimal disruption to ecosystems and local communities.
- Development of socio-economic tools combining land management and subsurface use.
- Development of environmental-socio-economic tools for strategic use of submarine nearshore and shallow marine geological domains.

Priority HER1 – Geoheritage and Geodiversity: A Strategic Asset for Europe

Europe's geological heritage and geodiversity constitute fundamental components of its natural capital and provide the physical foundation upon which ecosystems, landscapes, water resources, mineral resources, and human societies have developed. Geodiversity, defined as the diversity of rocks, minerals, fossils, soils, landforms and geological processes, represents the abiotic framework that underpins biodiversity, ecosystem services and environmental resilience. UNESCO⁶⁴ explicitly

recognises geodiversity and emphasises that the conservation of geodiversity is a prerequisite for the long-term protection of ecosystems and natural heritage. The UNESCO Global Geoparks programme provides one of the strongest international policy instruments supporting geoheritage and geodiversity. The growing recognition that “there is no biodiversity without geodiversity” provides a strong scientific basis for integrating geoscience knowledge into future environmental policies.

Within Europe, geoheritage and geodiversity contribute directly to several major policy objectives, including the European Green Deal, the EU Biodiversity Strategy for 2030, the Nature Restoration Regulation, the EU Soil Strategy and climate adaptation policies. Although geodiversity is not yet systematically addressed as a standalone policy domain, it is increasingly recognised as the abiotic foundation of ecosystems and landscape resilience.

Geoheritage also represents a strategic scientific asset for Europe, as preserved archives of unique records of past climate variability, sea-level fluctuations, environmental transitions and natural hazards. Geoheritage constitutes also a major asset for science education, tourism, and economic development. These unique sites are not only scientifically significant but also integral to preserving Europe's natural heritage. At the same time, many geoheritage sites are increasingly threatened by urbanisation, infrastructure development, resource exploitation and climate change, highlighting the need for coordinated monitoring, assessment and protection strategies at European scale. Geoconservation should be strengthened and better integrated into European environmental policies, recognising the importance of geological factors in the sustainable use of nature and in the conservation of natural heritage.

For Geological Surveys, geoheritage and geodiversity represent a natural extension of their public-service mission. Geological Surveys can provide the scientific basis required to identify, assess, monitor and valorise Europe’s geoheritage assets, through harmonised inventories, interoperable databases.

Action HER1.1 – Identify and Preserve Geoheritage Sites

Expected outcomes:

- Enhanced public and policymaker understanding of natural history, promotion of geosites for science, education and tourism, and contribution to sustainable land management.
- Protection of Europe’s geological treasures as part of its broader natural heritage.

Action HER1.2 – Integrate Geoconservation into Environmental Policies

Expected outcomes:

- Contribution and support to design environmental policies strengthening geodiversity and geoheritage in nature conservation programmes with a better alignment with biodiversity.
- Strengthened promotion of public awareness about the importance of geoheritage.
- Geoheritage to be considered in land-use planning and environmental assessments.

Action HER1.3 – Education and Public Engagement

Expected outcomes:

- Increased public knowledge and appreciation of geoheritage through educational programmes and geotourism initiatives, fostering stewardship of geological and natural heritage.

- Communities are empowered to engage in preservation of local geoheritage sites through targeted outreach and interactive learning experiences.
- A stronger connection between citizens and geological heritage, contributing to broader environmental consciousness and advocacy for conservation.

Action HER1.4 – Research and Interdisciplinary Collaboration

Expected outcomes:

- Better understanding of the interplay between geodiversity and biodiversity both onshore and offshore, particularly for biodiversity mapping, informing more effective environmental management and conservation policies.

DRAFT

GOAL: Societal and Economic Impact: Knowledge Sharing, Policy Support, and Public Engagement (SEI)

It is essential to harness and enhance Europe's geoscientific knowledge and expertise to address pressing challenges of the energy transition, environmental sustainability, geohazard risk mitigation and preparedness, and economic resilience, boosting the impact of our SRIA Goals. This requires concerted efforts to share knowledge and best practices across borders, engage the public, and ensure policies are supported by scientific data. By building a network that connects geoscientific and communication experts, educates the public, and informs policy, the Geological Service for Europe will be pivotal in supporting Europe's Clean Industrial Deal⁶⁵. This goal highlights critical areas of knowledge sharing, public engagement, and policy support to deliver societal and economic impact.

Priority SEI1 – A Network for Knowledge Sharing and Best Practices

NGSOs connect centuries of cumulative national data, information, and expert knowledge at continental scale – including through EuroGeoSurveys' 11 Expert Groups and 1 Task Force – to deliver a common pan-European geoscientific data and expert knowledge base. This includes the collaborative human network of thematic experts to inform consistent, holistic, science-informed policy across multiple sectors and policy areas. Relationships, communication, and best practices are central to accelerating the Clean Industrial Deal. Thus, it is crucial to strengthen our expert network, foster dialogue, and connect with communications specialists and ambassadors for geoscience with strong access points to stakeholder groups including academia, decision-makers and policymakers, industry, and the public.

Action SEI1.1 – Fostering Collaboration, Knowledge Sharing, and Geoscience Innovation to Support Europe's Industrial and Policy Efforts

Expected outcomes:

- An organised network connecting geoscientific experts with key stakeholder access points (e.g., ambassadors for geoscience, the media, educators, and public decision-makers).
- Accelerated energy transition and industrial projects: faster adoption of geoscientific data will reduce costs, improve resource efficiency, and minimise environmental impact.
- Standardised practices and improved data sharing: the creation of common standards for geological data management, subsurface exploration, and reporting ensures consistency across borders, fosters cooperation between nations and creates a unified approach.
- Improved global competitiveness and capacity building: Strengthened global geoscience partnerships, participation in international initiatives, support to capacity building in third countries, and an established knowledge-sharing network to ensure sustainable resource management and competitiveness and geohazard risk mitigation.

Priority SEI2 – Public Awareness, Engagement, Education, and Policy Support

EuroGeoSurveys and the NGSOs can further contribute to building public engagement and acceptance of controversial sectors, including mining and carbon storage, and underestimated sectors such as geohazards and geothermal. NGSOs have important roles to play in addressing social equity concerns, particularly in communities affected by resource extraction or land and subsurface use changes, by

engaging early and using tailored communication and knowledge co-creation. They can contribute to closing skills gaps in many geoscientific areas of expertise, notably critical raw materials, by supporting development and implementation of geoscience education programmes⁶⁶. These programmes should encompass a wide range of stakeholders including geologists, but also other sector-relevant professions, regulatory bodies, the media, and the public. By prioritising national training of geoscientists and associated professions, Europe can foster the emergence of a skilled workforce capable of meeting challenges and seizing opportunities presented by Europe's net-zero industrial ambitions.

Action SEI2.1 – Revitalising Geoscientific Expertise in Europe

Expected outcomes:

- Initiatives for engagement with educators and existing education initiatives to boost youth awareness of and engagement with geoscience education.
- Increased collaboration among geoscientific stakeholders.
- Stronger geoscientific competence in Europe.

Action SEI2.2 – Improved Geoscience Communication to Diverse Stakeholders

Expected outcomes:

- New and innovative mechanisms for engaging with stakeholders, with a focus on co-design.
- Audience-specific terminologies for improved communication outcomes.
- Translation of key documents for improved stakeholder dissemination.

Action SEI2.3 – Building Public Engagement for Sustainable Development

Expected outcomes:

- Public geoscience engagement at local to European scale, with direct stakeholder impact, particularly regarding resource extraction and changes in land and subsurface use.
- Improved public perception of geosciences and its application in diverse fields.
- Enhanced public engagement with key issues related to the energy transition.

Action SEI2.4 – Building Urban Resilience and Risk Awareness through Geoscience and Collaboration

Expected outcomes:

- Urban planners and communities will be better equipped to tackle geohazard and climate challenges, fostering resilience through knowledge-based decision-making.
- Enhanced risk awareness and collaboration between various stakeholders will ensure more effective risk management strategies.

Priority SEI3 – Policy Support Advice and Services

The Geological Service for Europe will improve pan-European harmonisation, standardisation, and knowledge sharing within and beyond the geoscientific community to underpin policy that will deliver resilient value chains, net-zero industries, and a sustainable environment and society. Increased availability, connectivity, and use of subsurface data are needed to inform the Clean Industrial Deal and related policy, serving as a basis for the expert services required to support policy implementation.

Expected outcomes:

- Informed policy decisions through enhanced data integration: policymakers will have access to harmonised, high-quality geoscientific data and models, enabling informed, evidence-based decisions. Data integration supports policy implementation in areas critical to Europe's environmental and industrial goals.
- Standardised frameworks for consistent policy application: the development of unified European standards will provide policy- and decision-makers with the tools to implement cohesive policies, reducing discrepancies between nations and fostering cross-border cooperation in areas such as energy, raw materials, sustainability, and risk management.
- Real-time decision support for crisis and risk management: policymakers and civil protection authorities will benefit from real-time tools and predictive models that provide timely insights during crises. These will help optimise government responses, minimise geohazard risks, and improve resilience to natural and industrial challenges.
- Accelerated implementation of strategic initiatives: streamlined processes and decision-support tools will enable policymakers to fast-track the development and implementation of projects aligned with the European Green Deal and other sustainability initiatives, ensuring quicker regulatory approval and infrastructure development.
- Data-driven solutions for long-term sustainability and resilience: by leveraging comprehensive data platforms, policymakers will be better equipped to design and implement policies that ensure sustainable management of natural resources, urban development, and environmental protection, aligned with Europe's long-term climate and industrial goals.

Conclusions

Europe is entering a period in which the sustainable management of its land, subsurface and geological resources will become increasingly critical to its environmental resilience, strategic autonomy and long-term prosperity. The green and digital transitions, European competitiveness in a critical geopolitical period, climate change, growing competition for resources, increasing pressures on land and subsurface space, and the need to protect ecosystems and natural capital are creating new and interconnected demands for geoscientific knowledge and expertise. In this context, understanding the Earth beneath and at the surface is no longer a specialised scientific requirement: it is a strategic capability for Europe.

The revised SRIA provides a framework for mobilising the collective scientific capacity of Europe's Geological Surveys organised through the Geological Service for Europe (GSE) to address these challenges. It builds on the fundamental role of Geological Surveys as custodians of long-term geological knowledge and public scientific expertise, while recognising the need to transform this knowledge into integrated, accessible, and policy-relevant information. Harmonised geological data, advanced mapping and modelling, Earth observation, monitoring, digital infrastructures, artificial intelligence, and interdisciplinary research will be essential to anticipate changes in the subsurface and to support evidence-based decisions. The European Geological Data Infrastructure and its evolution towards a more integrated and connected European geoscience knowledge system will therefore remain a fundamental asset of the Geological Service for Europe.

The strategic priorities identified in this SRIA – energy transition and decarbonisation, responsible and secure access to raw materials, sustainable groundwater management, geohazards and environmental risks, urban and territorial development, and the protection and valorisation of geoheritage and geodiversity – should not be considered as independent domains. They are closely interconnected through the multiple and sometimes competing uses of the subsurface. This integrated perspective will be essential for developing sustainable pathways for the use, protection and restoration of Europe's natural capital.

A key ambition of the Geological Service for Europe should therefore be to move from the production of geological information towards the delivery of integrated expertise dedicated to decision-support services. This requires stronger links between research, long-term observation, data infrastructures, and policy implementation, as well as closer collaboration with European institutions, national and regional authorities, academia, industry, and civil society.

The implementation of this SRIA will also require a sustained investment in scientific expertise and innovation. Strengthening European cooperation, sharing expertise and methodologies, supporting skills, and data infrastructures will therefore be essential components of the Geological Service for Europe.

Ultimately, the ambition of this SRIA is to establish subsurface sciences as a strategic component of European policy and decision-making. A permanent Geological Service for Europe, supported by a strong network of NGSOs, can provide the long-term, independent, and science-based knowledge needed to manage Europe's geological resources and environments responsibly.

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Glossary

Acoustic sensing solutions use sound waves to gather information about the subsurface (e.g. structure, properties, and dynamics of the Earth's subsurface).

Anthropogenic deposit is a material derived from human activities, including repurposed natural sediments (e.g., sand fill, soil enrichment) and newly formed substances.

Aquifer is a body of rock and/or sediment that holds groundwater.

Biostratigraphy is the branch of stratigraphy that uses fossils to establish relative ages of rock and correlate successions of sedimentary rocks within and between depositional basins.

Blue economy is the sustainable use of ocean, sea, and coastal resources for economic growth, improved livelihoods, and jobs while preserving the health of the marine ecosystem (<https://oceans-and-fisheries.ec.europa.eu/blue-economy>)

Brine is a highly saline aqueous solution, often containing minerals and other dissolved substances, typically found in underground reservoirs.

Building information modelling standard states that building information modelling is a digital representation of physical and functional characteristics of a facility.

Carbon Capture and Storage (CCS) is a three-step process, involving: capturing the CO₂ produced by industrial activity or power generation; transporting it; and then permanently storing it deep underground.

CO2GeoNet is the European network of excellence on the geological storage of CO₂ that is working on enabling the safe and efficient deployment of the CO₂ Capture and Storage (CCS) technology (<https://co2geonet.com/home/>).

Critical Raw Material (CRM) is a raw material that is essential for the economy but has a high risk of supply disruption. These are integrated in a list created by the European Commission of raw materials that are essential to the EU economy but have high supply risks (https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en).

Critical Raw Material Act (CRM Act) is a legislative act of the European Union aimed at ensuring a secure, sustainable, and resilient supply of critical raw materials necessary for Europe's economic and industrial needs. Its objective is to ensure that the EU can rely on strong, resilient, and sustainable value chains for critical raw materials enabling Europe to meet its 2030 climate and digital objectives (https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en).

Digital Twins are virtual representations of a physical object, system, or process that is continuously updated with real-time data. This digital model is designed to accurately reflect the state, behaviour, and performance of its real-world counterpart. These can be used to aid in understanding and forecasting geological events.

EC's DG ENV Working Group Groundwater is a technical group established by the European Commission's Directorate-General for the Environment (DG ENV) to support the implementation of the Water Framework Directive (WFD) and the Groundwater Directive (GWD) (https://environment.ec.europa.eu/topics/water/groundwater_en).

European Energy Research Alliance Joint Programme on Carbon Capture and Storage (EERA JP CCS) is a collaborative initiative aimed at accelerating the development and deployment of carbon capture and storage (CCS) technologies in Europe (<https://eera-ccs.eu/>).

European Geothermal Energy Council (EGEC) is a non-profit organisation dedicated to promoting the development and use of geothermal energy in Europe (<https://www.egec.org/>).

Electromagnetics surveys are techniques used to measure and analyse electromagnetic fields to identify and characterise subsurface features.

EMODnet is a European marine data infrastructure that provides free and open access to marine data and information collected by various European institutions and organisations. It aims to support sustainable marine management, research, and innovation by integrating data from different sources and making it easily accessible to users (<https://emodnet.ec.europa.eu/en>).

Environmental DNA (eDNA) is defined as the genetic material left by organisms in the environment.

Earth Plate Observation System European Research Infrastructure Consortium (EPOS) is a pan-European research infrastructure that provides open access to integrated scientific data and products for studying the Earth's solid interior, helping to understand and mitigate natural hazards like earthquakes, volcanic eruptions, and tsunamis (<https://www.epos-eu.org/>).

EU Blue Deal is a comprehensive strategy to address Europe's water challenges by promoting sustainable water management, protecting aquatic ecosystems, and ensuring water security for future generations (<https://www.eesc.europa.eu/en/initiatives/eu-blue-deal>).

EU Marine Strategic Framework Directive is the overarching environmental pillar of the EU's maritime policy. (https://research-and-innovation.ec.europa.eu/research-area/environment/oceans-and-seas/eu-marine-strategy-framework-directive_en)

EU Maritime Spatial Planning Directive establishes a common framework to organise the use of marine waters aimed to promote a sustainable development of the blue economy (https://oceans-and-fisheries.ec.europa.eu/blue-economy/maritime-spatial-planning_en)

EU Nature Restoration Regulation is a key element of the EU Biodiversity Strategy, which sets binding targets to restore degraded ecosystems, in particular those with the most potential to capture and store carbon and to prevent and reduce the impact of natural disasters (https://environment.ec.europa.eu/topics/nature-and-biodiversity/nature-restoration-regulation_en)

European Green Deal sets the goal of making Europe the first climate-neutral continent by 2050, while simultaneously resetting economic policy to support competitiveness, sustainability, efficiency, and resilience through a coupled green and digital transition (https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en).

European Earthquake Geology Task Force (EuQuaGe) is a group of experts that studies the geological factors contributing to earthquakes in Europe, aiming to improve earthquake risk assessment and mitigation.

European Ocean Pact is the European Commission comprehensive strategy to better protect the ocean, promote ocean research and a thriving blue economy and support the well-being of people living in

coastal areas islands and outermost regions. The legislative proposal designed to implement the Pact is the Ocean Act. (https://oceans-and-fisheries.ec.europa.eu/european-ocean-pact_en)

European Soil Observatory (EUSO) is a platform that provides comprehensive data, knowledge, and tools to support EU policies related to soil health and sustainability. It aims to safeguard soils, promote sustainable land management, and contribute to the European Green Deal (https://joint-research-centre.ec.europa.eu/eu-soil-observatory-euso/eu-soil-observatory-policy_en).

FutuRaM is a project that is developing a knowledge base on the availability and recoverability of secondary raw materials within the EU, with a special focus on critical raw materials (<https://futura.eu/>).

Geochemistry is the study of the chemical composition of the Earth and its materials, including rocks, minerals, water, and the atmosphere.

Geochronology is the study of the absolute age of geological materials and events, providing a timeline for the Earth's history.

Geoconservation refers to the actions taken to identify, protect, and sustainably manage geological sites, landscapes, and specimens with significant value for science, education, or tourism.

Geodiversity refers to the natural range (variety) of geological features, processes, and materials found in a given region.

Geoenergy refers to the use of heat and green energy, extracted from the Earth's subsurface, as well as CO₂ storage and clean energy carrier storage (e.g. hydrogen storage).

GeoERA was a European research project aimed at establishing a Geological Service for Europe. It focused on improving the understanding and management of the Earth's subsurface, particularly in relation to resources like geoenergy, groundwater, and raw materials. The project involved collaboration between various European geological surveys and research institutions (<https://geoera.eu/>).

Geohazards are natural processes or events that pose a threat to human life, property, or infrastructure due to their geological characteristics (e.g. earthquakes, volcanic eruptions, landslides, floods).

Geoheritage refers to geological features, landscapes, and sites that have significant scientific, educational, cultural, aesthetic, or historical value.

Geomechanics is the study of the mechanical behaviour of earth materials, such as rocks and soils, under various conditions.

Geomodelling is the process of creating and manipulating digital representations of the Earth's surface, including its features and processes.

Geophysical methods are techniques used to study the Earth's interior and its physical properties by analysing the behaviour of natural or artificially induced physical fields.

Geotechnical is a geoscientific domain that deals with the engineering behaviour of earth materials, such as soil and rock.

Geothermal refers to the heat stored in the Earth's crust, which can be extracted and used to generate electricity or provide direct heat.

Green Data4All Initiative aims to enhance environmental data sharing and public access to environmental information in the EU through updated regulations, promoting data-driven innovation and evidence-based decisions (https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13170-GreenData4All-updated-rules-on-geospatial-environmental-data-and-access-to-environmental-information_en).

Green Deal Dataspace is a federated ecosystem that provides access to projects and services related to resilience and sustainability, supporting the European Green Deal's goals (<https://green-deal-dataspace.eu/>).

Greenfield areas in mining refer to undeveloped land that is being considered or prepared for mining operations (started by a mineral exploration phase), often characterised by pristine natural landscapes and minimal existing infrastructure.

Groundwater defines the precipitation that has infiltrated the soil beyond the surface and collected in empty spaces underground.

Groundwater table is the upper boundary of the saturated zone in the subsurface where the pressure of the water is equal to atmospheric pressure.

Heat islands effects are urban areas that experience significantly higher temperatures than surrounding rural areas due to factors such as increased heat absorption from dark surfaces, reduced vegetation, and dense building structures.

Hydroclimatic refers to the interaction between hydrological processes and climate factors, encompassing the study of water cycle components (e.g., precipitation, runoff, evaporation) within a changing climate.

Hydrogeology is the scientific study of the distribution, movement, and quality of groundwater in the subsurface.

Lithogenetic units are fundamental rock bodies divisions based on their lithological characteristics, reflecting the depositional environments and geological processes involved in their formation.

Lithology refers to the physical characteristics of a rock, including its composition, texture, and structure.

Lithotectonic units are discrete, interconnected rock bodies that form the structural framework of the Earth's crust, defined by their lithological characteristics and tectonic history.

Metadata is structured information that describes, manages, and locates data, enabling its efficient access, use, and preservation.

Metallurgy is a scientific domain that study the structures and uses of metals.

Microgravimetric refers to the measurement of extremely small gravitational forces, often in environments where the Earth's gravity is significantly reduced or absent, such as space or deep underground.

MIN4EU is a European initiative that aims to provide a comprehensive database of mineral resources and information for decision-making in government and industry (<https://egdi.geology.cz/record/basic/5f8008e9-7928-4ef3-a0d2-42e70a010833>).

Mine dump is a large mound or hill of mining waste at the surface of a mine.

Mineral deposit is a naturally occurring concentration of a specific mineral or group of minerals in the Earth's crust that can be economically extracted.

Mineralogy is the scientific study of minerals, their composition, structure, properties, occurrence, and their formation.

Mining waste are the waste that occurs at several stages of the mining process and throughout all the life of the mine, from exploration (drilling) to mine closure.

Natural heritage refers to the biological and physical elements of the Earth, including ecosystems, landscapes, geological features, and species, that have significant ecological, scientific, or cultural value.

Net-Zero Industry Act (NZIA) aims to boost the EU's manufacturing capacity for net-zero technologies and their key components, addressing barriers to scaling up production in Europe and increasing CO₂ storage.

Ontologies represents the common scientific language that will be developed and adopted across geological surveys, ensuring consistent interpretation of geological data (https://single-market-economy.ec.europa.eu/industry/sustainability/net-zero-industry-act_en).

Pan-European of or relating to all European countries or the advocacy of political or economic unity among European countries.

Petrographic refers to the study of the microscopic composition and structure of rocks to identify minerals and their relationships within a rock.

Petrology is the scientific study of rocks and their formation, composition, and texture.

ProGEO is an international non-profit organisation dedicated to conserving Earth's geological heritage and promoting its importance for society (<http://www.progeo.ngo/>).

Quantum gravimetry is a method of measuring the acceleration of gravity using quantum mechanical principles, such as atom interferometry, to achieve unprecedented precision.

Quaternary is the current geological period, characterised by significant climatic fluctuations, the evolution of modern humans, and the development of complex societies.

Radiometric is a scientific field that measures and analyses the properties of radioactive materials, including their decay rates, radiation types, and energy levels.

Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) is an EU regulation that sets rules for the production, placement on the market, and use of chemicals in the EU.

Remote sensing is the process of detecting and monitoring the physical characteristics of an area by measuring its reflected and emitted radiation from a distance (usually from a satellite, aircraft and UAVs).

Renewable Energy Directive is an EU law that sets targets for the use of renewable energy sources across all sectors of the EU economy (https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en).

Reservoirs in geology are porous rock formations that store and transmit fluids, such as oil, gas, or groundwater.

SCRREEN is a project that aims to strengthen Europe's critical raw materials strategy by establishing an expert network to address issues related to mining, processing, recycling, substitution, and applications of these materials (<https://screen.eu/the-project/>).

Soil Monitoring Law establishes a framework for monitoring and improving soil health across the European Union to ensure it can provide essential ecosystem services and contribute to climate change mitigation and biodiversity conservation (https://ec.europa.eu/commission/presscorner/detail/en/qanda_23_3637).

Subsurface in geology refers to the layers of the Earth beneath the surface, encompassing rocks, minerals, and fluids that are not directly visible or accessible.

Unconventional deposits in mining refer to mineral resources that require specialised extraction techniques due to their unique geological characteristics, such as low-grade ores, difficult-to-access locations, or unconventional mineral forms.

Under-cover deposits in mining refer to mineral deposits that are located beneath a layer of overburden, often requiring advanced exploration tools to be detected and significant excavation or mining techniques to access.

United Nations Sustainable Development Goals (SDGs) define the fundamental policy targets and principles for coordinated actions across countries and between sectors (<https://sdgs.un.org/goals>).

Urban geology is the study of geological processes and materials within urban environments, focusing on their impact on infrastructure, land-use planning, and hazard mitigation.

Urban spatial planning is the strategic process of designing and managing the physical arrangement of land uses, infrastructure, and facilities within urban areas to achieve desired social, economic, and environmental outcomes.

Water Framework - Groundwater Directives aim to achieve good quantitative and chemical status of European water bodies through targeted measures including pollution prevention, monitoring, action programmes, and measurable objectives.

Water4All Partnership is a European initiative dedicated to ensuring water security for all through research and innovation (<https://www.water4all-partnership.eu/>).

WEFE Nexus approach highlights the interdependence of water, energy and food security and ecosystems.

Zero Emissions Platform (ZEP) is an advisor to the EU on industrial carbon management and aims to speed up the use of carbon capture and storage technologies in line with Europe's climate goals (<https://zeroemissionsplatform.eu/>).

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